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Significance of ZETA

SELDOM can a piece of scientific research have so captured the imagination of the whole country as that which has brought about the construction of ZETA and Sceptre III; seldom can the first tentative feelers into a new field of investigation have received such generous publicity. In part it is, of course, symptomatic of an international awareness of scientific developments, but also, together with antarctic peregrinations, represents this country's prestige answer to the U.S.S.R.'s and U.S.A.'s satellites.

Desirable as a more general understanding of science may be, we must be wary of " the little knowledge " which can result in such wrong impressions. It would be indeed churlish to minimize the achievements of the teams which have constructed these machines and no doubt the 1957 experiments will rank for all time in scientific history as amongst the great, but we must keep this subject in proper perspective.

The golden hope that thermo-nuclear fusion offers is unlimited power for as long as we can contemplate. To our grandchildren's grandchildren this may be of overwhelming importance, but we must emphasize that to date, particularly in peace time, availability of fuel has never been a limitation to industrial progress. Power itself is certainly a deciding factor in industrial development and even agricultural development, but the limitation has always been one of cost and not simply of raw materials. This picture will no doubt change as demands increase and become more uniform throughout the world but it will not be for some years yet.

The Harwell and Aldermaston experiments are only the first steps along the road towards harnessing nuclear fusion for power applications. Before the break-even point is reached the power-in to power-out ratio must improve by a million million—no mean factor. Calculations indicate a temperature of around 500 million degrees must be reached before fusion becomes a practical proposition, that is one hundred times the temperature achieved so far. The trials and tribulations that will be met on the way are impossible to foresee but there is little doubt that they will be formidable. It is by no means certain that engineering and materials limitations may not force us to conclude that an energy gain in the fusion process is in practice impossible. Certainly a very great deal of development lies ahead and much more must be known about plasma physics before any confident predictions, even, can be made about the future.

A second hope of fusion lies in the possibility of extracting energy from the plasma directly as electrical energy without the need for a heat cycle. There appears to be no conceivable way of permitting the neutrons to contribute in this way and the maximum thermal efficiency that can theoretically be achieved with the DD reaction is only 66% and only 20% for the DT reaction —even assuming there are no disadvantageous side reactions and that radiated power and input power are negligible in comparison with reactor output power. It is probable (although all speculation at this stage is dangerous) that the heat engine will ultimately show up very favourably with the direct system and it is almost certain that heat transfer will be as important in the technology of fusion as it is for fission reactors.

Nevertheless, it is proper to consider the question, when companies who are investing large sums in fission reactor developments should begin to take account of thermo-nuclear developments. Sir John Cockcroft, although naturally somewhat hesitant to commit himself, when pressed upon this point has suggested that a minimum period of five years must elapse before even long-term developments should be affected by the ZETA programme. The thermal neutron reactor projects, he believes, will not be influenced by fusion developments although it is probable that fast reactor philosophy will be modified.

This is not to be interpreted as implying that at the end of five years fission reactor developments should cease, but rather that the Harwell results as they come along should be studied and only at the end of five years is it likely that these results can assume significance in relation to long-term projects then being planned.

If a Gallup poll were taken of those working on the thermo-nuclear experiments to obtain a guess as to when (if ever) the first reactor would be built which gave a positive energy gain, there would undoubtedly be a very large spread in the answers with perhaps 15 years coming somewhere near the mean. No doubt, grouping into physicists and engineers would show a larger figure for the second group! Another poll on cost per kWh. would almost certainly result in such a large proportion of " don't knows " that the analysis would be meaningless. Fascinating although this whole subject is, we can at present only wait and see.

Staff Changes in the A.E.A.

IN our February issue we published a summary of the findings of the first two Fleck committees dealing with general organization and organizing for the control of health and safety (page 46). At the end of January it was announced that the first steps had been taken to implement the recommendations concerning the structure of the Authority which consists of a chairman appointed by the Prime Minister, and 10 members, five full-time and five part-time. The Fleck report recommended that the full-time members of the Authority should not, in addition to these duties, carry executive responsibility for a particular establishment and Sir John Cockcroft has therefore relinquished his post as Director of A.E.R.E. Harwell, and has been succeeded by Dr. B. F. J. Schonland, the previous deputy director. The permanent member of the Authority for engineering has also now been appointed, Sir William Cook, previously deputy director of A.W.R.E., and although Sir William Penney continues as member for weapons research and development, and also as director of A.W.R.E., this is a temporary measure only.

Now a number of further changes have been announced and, although some are entirely as expected, others demonstrate the difficulties that the Authority must meet in finding suitable men within its own ranks. We should have thought more effort would have been made to attract outside men so that the experience gained in the organization and operation of other large industrial groups would have been available. Such men are, of course, not easy to come by and bringing in people at the top can have repercussions below. The A.E.A., however, can hardly be accused of meanness in its attitude towards promotion and, although there is a widespread belief that the Authority's staff is underpaid in comparison with industry, in the main this is not true. There is a difference at director level, but, for the lower ranks, salaries throughout the U.K.A.E.A. compare favourably with those paid in industrial concerns involved in nuclear energy developments, and generously with most other industries.

Nuclear energy is a young subject and is being largely developed by people who are also young, but organization and the operation of a complex industrial plant demands a great deal of experience and a wide knowledge of industrial problems; experience cannot be developed overnight simply by promotion.

Insurance Plans

THREE moves have been made in the past month to formulate permanent plans for the insurance of reactor risks. In this country the Government has announced that, in the next session, it is proposed to introduce a Bill to ensure by a system of licensing and inspection that land-based reactors are made effectively subject to control in the interests of public safety. Reactor operators will be required to insure or hold liquid assets to cover compensation up to a limit of £5 million, a figure which they are advised is more than adequate to cover any reasonably foreseeable risk. These measures will affect both industrial operators of reactors and the electricity authorities, providing the latter adhere to their tradition of insuring in the normal insurance market. The Bill follows closely the recommendations made by the committee set up by the British Insurance Association and Lloyds. The British Insurance Atomic Energy Committee speaking for the insurance companies and Lloyds will no doubt be responsible for giving quotations and the Industrial Group Health and Safety Branch for licensing and inspection. The A.E.A. itself is unlikely to seek insurance outside the Treasury although it will still be controlled by the same health and safety regulations.

In the United States discussions are proceeding with a view to preparing a more comprehensive permanent regulation than that contained in the temporary regulations issued on September 11, 1957. It is expected that the $500 M. indemnity offered by the Commission to licensed reactor owners will be extended to Commission prime contractors and their suppliers, and possibly to other contractors engaged in activities involving the risk of occurrence of a substantial nuclear incident. Existing indemnity provisions do not cover nuclear accidents that are caused by the fault or negligence of the subcontractor or supplier. It is likely that this rule will be modified to cover all eventualities.

An O.E.E.C. group of experts of the newly set up European Nuclear Energy Agency is to seek common European regulations for third party liability in the field of atomic energy. It is hoped that a uniform policy throughout Europe can be arrived at.

It is interesting to compare the two figures being quoted in the U.S. and the U.K.—$500 M. as against £5 M., but there is a difference in approach and it would be unkind to suggest that this represents the difference in safety between the pressurized water reactor and the gas-cooled graphite moderated reactor. It should be pointed out that the regulations concerning insurance refer to third party liability only. Insurance for the plant falls into the same category as normal industrial insurance. Also, it might, at first sight, seem unreasonable that owners of large power stations should not have to insure for a greater amount than operators of small or research reactors. Given a catastrophe in the two cases, there is no doubt that the power station could cause very much more widespread damage than, say, a small swimming pool reactor, but this will be taken into account in the assessment of premiums, and if for a particular plant the maximum third party risk is considered to be, say, £100,000, the difference in premium for insuring this figure as against £5 M. will be small.

Commentary

ZETA—Future Programme

The first major task that faces experimentalists both in this country and in the United States is to establish definitely the mechanism by which the neutrons are produced. Although at first sight the reasonable correlation with theory would indicate a fairly high degree of certainty in a thermo-nuclear origin, there have already been a sufficient number of disappointments in this particular field of research for individual workers to be most chary of making unsubstantiated claims. It is essential for a firm identification of the source that the total number of neutrons produced per pulse should be increased and the first step in ZETA at least will be to attempt to increase the temperature. There is every reason to suppose that this can be done by increasing the condenser bank and therefore the total energy injected into the plasma. At the present point of probable operation, on the energy cross-section curve, quite small increases in temperature should greatly increase the neutron production, but although a significantly increased total number will be further indication that the neutrons are thermo-nuclear produced, only a measurement of the energy spectrum which can be compared with the spectrum produced by accelerator machines can establish whether the reacting nuclei have random direction and a Maxwellian energy spread. Changing the gas to a mixture of deuterium and tritium should also yield convincing proof, but with an apparatus like ZETA the decision to fill with a radioactive gas cannot be taken lightly and additional safeguards must be installed to prevent any health hazard.

At the same time, a long period of research is ahead aimed at increasing our understanding of the physics of plasmas. In the United States greater attention has been paid to the theoretical approach to the problem than in this country, where a more empiric approach has been practised. This is somewhat contrary to tradition in the two countries, but on both sides of the Atlantic it is necessary that a great deal of effort be now expended on building up a sound theoretical picture of plasma behaviour. A totally ionized gas must be considered as a fourth state of matter and, although a great deal has been learnt about the physics of stellar bodies, our terrestrial experience of plasma is small.

Following this increase in knowledge of plasma physics, no doubt it should be possible to raise again the temperatures and also to increase the time over which a plasma can be held confined. Although 5M°K is an impressive figure, we are still only at one-hundredth of the temperature necessary to reach the break-even point. In terms of power output, a factor of something like 10^{12} is required before our input/output ratio becomes reasonable.

The engineering difficulties that will be met on the road towards this goal are certainly going to be considerable. Even at the present input energies, electrical breakdowns have not been eliminated and, with increasing temperatures and increasing electrical fields, these are likely to become very much more severe. This is not a new problem to the electrical engineer and steady progress has been made in this field during this century, but we are already working near the limit of our knowledge and the development that is necessary before significant advances can be made is likely to be formidable. It is even possible that this problem alone will prevent the practical utilization of thermo-nuclear fusion. As in the fission field, the metallurgist can have a great influence on future developments. Although with ZETA and with Sceptre III aluminium has proved to be a satisfactory material for the torus, increasing temperatures will almost certainly call for more exotic constructional materials. Sir John Cockcroft has indicated that it is unlikely that small thermo-nuclear reactors can be built and that installations will be large. If very large vacuum toruses have to be built in materials like niobium, not only is the cost going to be considerable but technologies in these materials will have to advance a great deal. It is possible that cermets will find a place in this field and certainly the techniques of jointing high-temperature conducting and non-conducting materials will have to be developed. Even supposing the direct conversion of part of the energy in the plasma into electrical energy becomes a practical proposition, there is nevertheless certain to be a high flux of energy to the walls of the container from neutrons and Bremsstrahlung. It is possible that these heat fluxes will be so large in any apparatus which approaches economic generation that conventional systems of heat removal will be inadequate and the technologies of liquid metal cooling which have proved so troublesome in the fission field will be of even greater importance in the thermo-nuclear fusion field.

Uranium Agreements

An assessment of the probable influence of ZETA developments on the fission programme can be obtained by a study of recent uranium contracts that have been signed between the United Kingdom authorities and Canada. Previous agreements called for the delivery of over $100 million worth of uranium by April, 1962, and it is understood that the new agreement covers a further $100 million worth of Canadian uranium to be delivered over the following 12 months. It is understood that negotiations are proceeding for the sale of substantial quantities over the course of the next three years. Production in Canada has been steadily increasing and it is expected that, by the end of this decade, annual production will total over 15½ thousand tons. Although uranium prices have been fixed, so that plant can be written off in a fairly short time, mining interests have been greatly concerned by the possible decreasing market in the 1960s. These new moves should do much to reassure uranium producers that they are unlikely to be put out of business by thermo-nuclear developments for some time yet. In addition to the

Canadian agreements, it is understood that the U.K. and U.S. authorities are to visit South Africa shortly to discuss uranium production and the possibility of increased output.

A.E.C. Organizational Changes

The A.E.C. has made a series of changes in its organizational structure to separate the regulatory from the non-regulatory functions in its civilian application programme. The Division of Civilian Application has been abolished and in its place have been established the Division of Licensing and Regulation, which will handle all licensing and regulatory functions previously handled by the Civilian Applications Division, and a new office of Industrial Development with responsibility for developing overall Commission policy to encourage and assist in private activities in the civilian applications of atomic energy. The Industrial Development office will advise private groups on opportunities which appear to be open to them and will seek to identify industrial activities including those now performed by the Commission, which lend themselves to private undertakings and will assist in encouraging industry to enter these fields. A major function of the office will be the development of programmes to accelerate the use of radioisotopes and applied radiation in industry, agriculture and medicine, and to encourage industrial production and the distribution of isotopes and other radiation sources.

Other organizational changes can be expected in the near future because of the growing unrest in industry concerning the large investment programmes that are demanded and the uncertain ultimate value of this investment. The political squabbles of 1957 concerning the proper place of the A.E.C. in the civilian power programme would appear now to be somewhat academic, as reluctance on the part of industry to sink very much more capital into atomic energy will force the federal government to take over greater responsibility for developments.

HAR Proposal

The Pennsylvania Power and Light Company and Westinghouse Electric Corporation have proposed in response to the invitation issued by the Commission in January, 1957, under its power demonstration reactor programme the construction of a nuclear power plant utilizing a single zone homogeneous reactor. The proposed plant operating on the thorium/uranium cycle would have a generating capacity of from 70 to 150 MW electrical. The proposal asks as a first step A.E.C. payment during 1958/59 for further research and development, the costs so far on this project having been borne entirely by the utility-manufacturing team, totalling $5½ million to date. The second step to be reached in December, 1959, calls for a decision either to begin actual construction of a nuclear power plant to be completed by the end of 1963 or the termination of the project. Recently the Baltimore Gas and Electric Company joined the reactor project group. If A.E.C. agrees, costs during the pre-construction period would come to $7.3 million and the second step contemplates a further amount not to exceed $18 million. It is believed that a power plant could be constructed for $380 per kW.

Shortly after this proposal was received, the A.E.C. announced that HRE 2, an experimental power reactor, at Oak Ridge had achieved criticality on December 27. The thermal rating is 50 MW and the electrical capacity, 300 kW.

In view of the corrosion problems now known to be associated with the development of the HAR, the proposal by the groups is perhaps somewhat surprising. It will be remembered that re-calculation of the expected costs on the Wolverine reactor caused this project to be abandoned in the middle of last year. The A.E.C., however, is anxious to evaluate the practical potentialities of the HAR and experience on HRE 2 together with this further research should enable it to make a realistic appraisement of the system by the end of 1959.

Sodium Cooled Epithermal Reactor

Following the successful start-up of SRE, Atomics International Division of North American Aviation Inc. has reiterated its faith in sodium cooling by undertaking a reactor study dubbed the Advanced Epithermal Thorium Reactor. The study, which is for the South West Atomic Energy Associates, composed of 15 investor-owned electricity companies has been agreed by the A.E.C. as a logical extension of work now in progress in the Commission's programme. A $5½ million four-year research and development programme is planned with a view to the construction of one or more full-scale nuclear power plants.

The AETR contemplates the use of sodium as coolant, U233 as fuel and, if moderated, beryllium or graphite. Power stations of 200 MW output are envisaged.

Chemical Energy Storage

An interesting approach towards the problem of energy storage is disclosed by the U.S.A.E.C. announcement that it has contracted with Rensselaer Polytechnic for further research in radiation chemistry by Doctor Paul Harteck and associates in the department of chemistry. $191,000 has been made available to the institute to defray the costs of the investigation through next June. Experiments concern the use of fuel elements composed of filaments of glass in which uranium-oxide is incorporated, the heat produced being utilized to generate nitrous oxide from compressed air. So far, studies have revealed (*Nuclear Engineering*, February, 1958, p. 47) that only pumped water storage offers a reasonably economic method of increasing the load factor of nuclear power stations.

Geneva Papers

Further investigation reveals that we were probably somewhat hasty in our judgment, in January, when we accused the A.E.A. of regarding the Geneva Conference as a " private show." Certainly, there still remains a great deal of dissatisfaction with the British representation, but proper machinery is in existence for joint consideration of submitted subjects. That the representations of the various organizations, concerned with the promotion of contributions, did not seem to operate very effectively is regrettable, although perhaps understandable when bearing in mind the great divergency of interest and the large number of individuals who are concerned with atomic energy developments. It would appear also that, although the contributions from industry will not be negligible, the response was disappointing and by no means as great an effort has been made as commercial and prestige considerations would indicate desirable.

By a regrettable mistake, the illustration of Berkeley power station on p 67 of our February issue was credited to " John Thompson/Simon-Carves." The caption should, of course, have read "A.E.I.-John Thompson Nuclear Energy Co. Ltd."

THERMO-NUCLEAR FUSION

A Survey of the Position

Thermo-nuclear research was originally carried out in Britain by two groups at the Clarendon Laboratory, Oxford, and at Imperial College. In 1951, for reasons of security, the Clarendon Laboratory team was transferred to A.E.R.E., Harwell, and the Imperial College team to the A.E.I. research laboratories at Aldermaston. The work of the two teams has resulted in the toroidal discharge machines ZETA and SCEPTRE respectively.
In the U.S.A., thermo-nuclear research was started somewhat later than in the U.K., but has grown rapidly over the past few years. Project "Sherwood" co-ordinates the work of a number of establishments, but the Los Alamos group is the most important. E.D.F. is also carrying out experiments in France, and promising results have also been reported from Germany and Sweden.
With the general relaxation of restrictions, it is now possible to publish more detailed information on the subject.

1. Theoretical Considerations

As early as 1934 a great deal was known about the reaction which took place when deuterium ions accelerated in a high-voltage machine, were allowed to strike a target of heavy ice. If the accelerated ion is given an energy of several tens keV, sufficient to overcome the electrostatic repulsion which it encounters as it approaches a similar positively charged nucleus, a neutron can be produced carrying nearly 2½ MeV of energy. In addition kinetic energy is imparted to the transmuted nucleus. Energy gain can be as high as a factor of 300. Unfortunately the fraction of the bombarding ions which interact with the target nucleii to undergo fusion is small, the vast majority of ions dissipating their energy in electron collisions and other unproductive processes. The result is a very considerable overall energy loss; for example, with a current of 0.1 amp/cm² in the bombarding beam—a fairly high current in terms of conventional accelerators—the energy released as a result of fusion is around 50 μW/cm² in the target. Although the DD reaction initiated by accelerator techniques has provided a valuable source of mono-energetic neutrons for research purposes, the process offers no opportunity for generating power.

The DD reaction is not the only reaction which could conceivably be used for the generation of power, and Table 1 lists those which could be considered in this context. It must be remembered, however, that the greater the charge on the nucleii the greater is the electrostatic force resisting fusion and the greater the energy that must be imparted in order to bring two nucleii together. As a result, the DD and the TD reactions have received most attention. Fig. 1 gives the cross-sections for these two reactions against energy of the bombarding nucleus. The DD reaction can proceed in two ways; either forming helium-3 plus a neutron or tritium and a proton and these two reactions have approximately the same probability. At first sight it might appear that as the TD reaction gives a greater yield that this would have received the greatest investigation, but tritium is radioactive which introduces

Table 1. Fusion Reactions

1.	D	+ D →	He^3	+ n	+	3.25	MeV
2.	D	+ D →	T	+ p	+	4	MeV
3.	T	+ D →	He^4	+ n	+	17.6	MeV
4.	He^3	+ D →	He^4	+ p	+	18.3	MeV
5.	Li^6	+ D →	$2He^4$		+	22.4	MeV
6.	Li^7	+ p →	$2He^4$		+	17.3	MeV

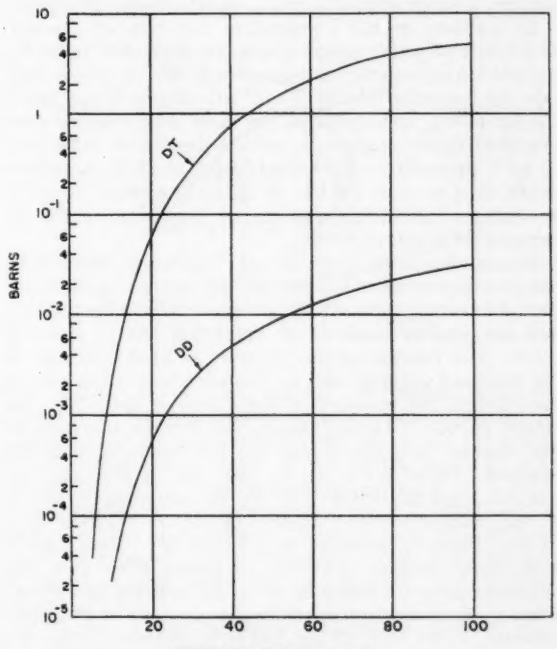

Fig. 1.—Nuclear fusion reaction cross-sections as a function of relative particle energy.

practical complications and, in addition, the bulk of the energy is liberated in the neutron which, as will be seen later, has certain disadvantages.

The most direct approach towards the practical utilization of the fusion process for power generation is to create a condition where thermo-nuclear processes can go on. In thermo-nuclear fusion the energy of the bombarding nucleus is solely derived from its kinetic temperature energy. An examination of the relationship between temperature and kinetic energy immediately shows that very high temperatures are required. Assuming a gas has reached equilibrium conditions and the energy distribution amongst the component particles can then be considered Maxwellian, the main particle energy W equals $3kT/2$. A common way of expressing temperature is as kinetic temperature where 1 keV equals 11.6M°K and the mean particle energy is

then 1.5 keV. In other words, if the temperature is 5M°K then the kinetic temperature equals 0.43 keV and the mean particle energy is 0.65 keV. Referring then to Fig. 1, it is clear that a reasonable cross-section for the DD reaction can only be achieved at a temperature exceeding 100M°K. At lower temperatures the cross-section is critically dependent upon energy; once thermo-nuclear processes have been induced only small increases in temperature should increase the reaction rate by a very great amount.

The various experimental machines that have been built in this country and the United States, to investigate thermo-nuclear processes have succeeded in generating neutrons with temperatures believed to be around 5M°K. It has not been proved conclusively that these neutrons or what fraction of these neutrons are genuine thermo-nuclear produced, but the numbers correspond reasonably with theoretical predictions. It is only of course because of the Maxwellian spread in energies that any reactions are proceeding at all. Calculations indicate, for example, that with a temperature of 12M°K the bulk of the thermo-nuclear reactions is produced by particles which have energies of eight times the mean particle energy or greater.

In addition to the temperature the rate of reaction or the rate of power generation is also dependent upon the particle density—being proportional to n^2. If power outputs of the order of 100 W/cm^3 are required, this figure corresponding approximately to those obtaining in conventional fission reactors, a particle density of from 10^{-4} to 10^{-5} atmospheric is required which at 150M°K corresponds to a pressure of 100 to 10 at and means must be devised for containing the gas at this pressure for an appreciable length of time.

Before discussing methods of producing these high temperatures and containing the gas some consideration should be given to the distribution of energies in the reaction and the possible methods of converting this to a useful form. The released energy appears as kinetic energy of the resultant particles and as momentum is conserved in the reaction the majority of the energy is carried by the lighter particle. Table 2 details the energies imparted to the reaction products in the two DD reactions and DT reaction. From this it can be seen that of the total DD reaction approximately 66% of the reaction energy is passed to the charged particles whereas in the DT reaction 80% of the energy is imparted to the neutron. Theoretically it should be possible to extract the energy direct from the reacting gas by causing it to act as the primary of a transformer. High conversion efficiencies can only be obtained, however, if the bulk of the energy is retained within the gas and there seems little likelihood of containing the neutrons. The DD reaction therefore offers a possible thermo-dynamic efficiency of 66% neglecting radiation losses whereas the maximum possible direct conversion efficiency for the DT reaction is only 20%. At the same time, if a continuous reaction is to be produced then the side reactions must be considered including the DT reaction with the tritium formed in the first of the DD processes. If equal probability is allowed for the two DD processes and the subsequent DT process is added into the equation, then the reaction can be rewritten

$$5D = He^3 + He^4 + p + 2n$$

and only 33% of the energy is transferred to the charged

Table 2. Energy Partition

DD →	(T + 1.0 MeV) + (p + 3.0 MeV)
DD →	(He^3 + 0.8 MeV) + (n + 2.45 MeV)
DT →	(He^4 + 3.6 MeV) + (n + 14.1 MeV)

Une déclaration en commun a été publiée par le Royaume Uni et les Etats-Unis sur le déroulement des travaux d'expériences visant à l'utilisation de la fusion nucléaire pour la production d'énergie. Les calculs indiquent qu'avant que l'énergie produite dans un gaz chaud composé de deuterium puisse égaler les pertes par radiation, des températures de plusieurs çentaines de millions de degrés doivent être obtenues.

Deux machines qui soutiennent une décharge de courant élevée stabilisée ont été construites et mises en fonctionnement en Grande Bretagne, et des températures atteignant 5M°K ont été spectographiquement mesurées. Dans le ZETA, construit à Harwell, la décharge est produite dans un tore en aluminium, de diamètre moyen de 3 m, et d'un diamètre axial de 1 m, enfilé par deux noyaux de fer cylindriques. Des enroulements primaires sont impulsés d'un assemblage de condensateurs de 1600 μF chargés à 25 K.V. Un champ magnétique axial de 160 gauss stabilise la décharge de courant de pointe de 200 K.A. pendant plusieurs millisecondes. Le SCEPTRE III, construit dans les laboratoires d'études de la Compagnie A.E.I. Ltd., est analogue en principe, mais plus petit; le diamètre moyen est de 115 cm, le diamètre axial de 30 cm, et les enroulements primaires entourés autour du tore plutôt que du noyau sont alimentés d'un assemblage de 150 μF chargé à 30 K.V. Un champ axial de 500 gauss stabilise la décharge pendant 300 sec. Dans les deux machines, les neutrons sont produits à des moments correspondants au courant plasma et en des quantités qui sont compatibles avec une origine thermo-nucléaire.

England und die Vereinigten Staaten von Amerika haben eine gemeinsame Erklärung über den Fortschritt veröffentlicht, der in den experimentellen Arbeiten, die als Ziel die Ausnutzung der Fusion von Atomkernen zur Krafterzeugung haben, gemacht worden ist. Berechnungen zeigen, dass, bevor die Energie, die in einem heissen Gas aus schwerem Wasserstoff (Deuterium) erzeugt wird, die Verluste, die duch Srahlung entstehen, ersetzen kann, Temperaturen, von mehreren hundert Millionen Graden erzielt werden müssen.

In England sind zwei Maschinen gebaut und in Betrieb genommen worden, in denen eine Entladung von hoher Stromstärke stabil gehalten wird, wobei Temperaturen bis zu 5 Millionen Grad K spektrographisch gemessen worden sind. In „Zeta", der in Harwell gebauten Maschine, wird die Entladung in einem hohlen Aluminium Ring von 3 m mittlerem Durchmesser und 1 m achsialem Durchmesser erzeugt, der von zwei zylindrischen Eisenkernen durchsetzt ist. Die Primärwindungen erhalten die Pulse von einer Reihe von Kondensatoren von 1600 μF, die mit 25 kV aufgeladen werden. Ein achsiales magnetisches Feld von 160 Gauss hält die Höchststrom-Entladung von 200 kA während mehrerer tausendstel Sekunden stabil. „Sceptre III" ist in den Forschungslaboratorien der A.E.I. Ltd. gebaut worden und im Prinzip ähnlich, jedoch kleiner; mittlerer Durchmesser 115 cm, achsialer Durchmesser 30 cm; den Primärwindungen, die um den Hohlring gelegt sind, und nicht dem Kern wird der Strom von einer Reihe von Kondensatoren von 150 μF, die mit 30 kV aufgeladen werden, zugeführt. Ein achsiales Feld von 500 Gauss hält die Entladung 300 Sekunden lang konstant. In beiden Maschinen werden Neutronen erzeugt in Perioden, die dem Plasma Strom entsprechen, und in Mengen, die sich aus dem thermo-nuklearen Ursprung ergeben.

Se ha publicado un informe colectivo en que el Reino Unido y los Estados Unidos dan cuenta de los progresos alcanzados en trabajo experimental cuyo objeto es el de utilizar la fusión nuclear para la producción de energia. Los cálculos muestran que antes de que la energía producida en un gas caliente compuesto de deuterio puede igualar las pérdidas de radiación hay que alcanzar temperaturas de varios millones de grados.

En este país se han construido y se han operado dos máquinas que soportan una descarga de corriente elevada estabilizada, y han sido medidas espectográficamente temperaturas hasta de 5M°K. En ZETA, construida en Harwell, la descarga se dispone en un toro de aluminio, diámetro medio de 3 m y diámetro axial de 1 m enhilado por dos núcleos cilíndricos de hierro. Los arrollamientos primarios son pulsados de un banco de 1600 μF de condensadores cargados a 25 kV. Un campo magnético de 160 "gauss" estabiliza la descarga de corriente máxima de 200 kA durante varios milisegundos. SCEPTRE III, construida en los laboratorios de investigación de la A.E.I. Ltd. es similar en principio pero más pequeña; diámetro medio 115 cm., diámetro axial 30 cm. y las vueltas primarias arrolladas alrededor del toro mas bien que el núcleo son alimentadas de un banco de 150 μF cargado a 30 kV. Un campo axial de 500 gauss estabiliza la descarga durante 300 segundos. En ambas máquinas los neutrones son generados a tiempos correspondientes a corriente de plasma y en cantidades que son consistentes con un origen termonuclear.

particles. This, it should be noted, however, ignores the side reactions with helium-3 and other side reactions which would no doubt take place in a system allowed to go to equilibrium. Energy transferred by the neutron would not necessarily be lost entirely and could be absorbed in a heat transfer fluid and utilized in conventional heat cycles. It must be emphasized, however, that in this early stage of development the whole subject of power utilization is highly speculative and it is quite possible that engineering considerations will ultimately be overriding.

In addition to the energy carried away from a reacting system, by the uncharged particles, some radiation is, of course, inevitable. If the classical black body radiation laws applied, then there would be no point in pursuing the thermo-nuclear programme as a system of enormous dimensions would need to be built before reaction rates could equalize radiation losses. This argument is somewhat specious as also the sun would have long ago radiated its energy and the problem would not arise. For a completely ionized gas the radiation power is more nearly proportional to $\sqrt{T}$ and is also proportional to the square of the atomic number of the gas. The bulk of the radiation is in terms of Bremsstrahlung generated by decelerations of electrons. The dependency upon Z^2 indicates the importance of high purity in the gas as quite small contaminations of high atomic number atoms can considerably increase the radiation losses. It should be noted, nevertheless, that in ZETA significant additions of oxygen and nitrogen have been made for temperature measurements and surge suppression. The radiation power is also dependent upon the particle density and is, in fact, proportional to n^2, i.e., the same as rate of power generation. Strictly the radiation loss is proportional to the square of the number of electrons and the power generation proportional to the square of the number of ions, but when neutral atoms are the fuel feed these two figures can be taken as being equal. The break-even point, therefore, when power generated equals radiation loss can be defined in terms of temperature only and is not affected by the geometry. For the DD reaction the calculated figure is in the region of 35 keV kinetic temperature or 400M°K and for the DT reaction, because of the greater cross-section, is in the region of 50M°K. As mentioned above the radiation loss is in the form of relatively low energy Bremsstrahlung and can be readily absorbed in a suitable heat transfer medium.

Two types of apparatus have been used to investigate gases at these high temperatures. The first is a linear device in which a high current discharge is passed through a gas between two electrodes and the second a toroidal system in which a heavy current discharge is induced in a gas confined in an anchor ring. The second system is the basis of the two British machines ZETA and Sceptre III whilst the work reported by Kurchatov at Harwell in 1956 and the bulk of the American work have been performed on linear devices. When a high current discharge is initiated in a gas the bulk of the energy is imparted to the electrons around the periphery and a magnetic field is created which is in such a direction as to cause an inwards pressure on the gas (Fig. 2). A more familiar example of this effect is the force of attraction between two parallel conductors carrying current in the same sense. When the magnetic force exceeds the gas pressure, the well-known pinch effect takes place in which the gas contracts into a pencil at the same time undergoing adiabatic heating. During this time energy is being transferred to the ions but the detailed mechanism of this is not understood as the rate of energy transfer experienced is significantly higher than theory would predict. At temperatures of over a million degrees the gas is almost completely ionized but there is no macroscopic separation of the ions and the electrons and the plasma can be considered electrically neutral. The pinch effect has received considerable study over the past years and much theoretical and experimental work has gone into the examination of instabilities that occur. Unfortunately, immediately the pinch is established, any small kink occurring in the filament causes a local increase in the magnetic forces and, therefore, an increase in the magnetic pressure which tends to further distort the beam. The result is that if no stabilizing forces are applied, the kinks increase and finally touch the walls of the containing vessels whence the plasma is rapidly cooled and the pinch disappears.

The great step forward that has been made in ZETA is stabilizing the pinch for appreciable periods of time, by the application of a magnetic field in the direction of the plasma current. The field is applied before the current discharge and when the pinch occurs the field is trapped within the pinch. It acts in much the same way as tension bands through the filament resisting the tendency to kink. In time, this field will diffuse out of the plasma and calculations indicate that the diffusion period for the ZETA experiment would be about one second. At present levels of operation in ZETA a field of something like 160 gauss is required. By the application of this axial field the pinch has been maintained stable in the ZETA apparatus for periods of several milli-seconds as opposed to a few micro-seconds for an unstabilized pinch. Applications of similar fields to linear devices, although partially successful cannot be expected to give long-term stabilization because of the poisoning effect of the filament striking the electrodes.

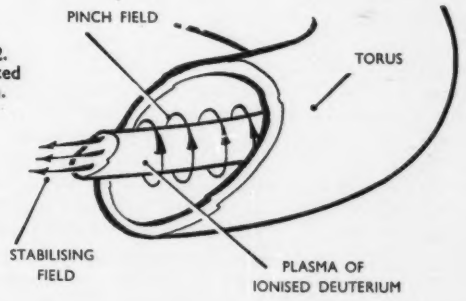

Fig. 2. Stabilized pinch.

A further stabilizing effect is given by eddy current formation in the walls of the containment vessel, generating forces which resist the "approach" of the filament. The extent of the contribution of this effect to the overall stability is not fully understood.

Although it has yet to be proved that thermo-nuclear fusion has been achieved, there is no doubt that the source of neutrons is a DD reaction but in these intense magnetic fields, strong local electric fields can be set up which are sufficient to accelerate ions out of the filament which then strike the walls of the vessel which contain adsorbed deuterium. When the rate of neutron production is sufficiently high for "good counting statistics" to be obtained, the energy spread of the neutrons will show whether the average centre of mass of the reactions corresponds to a random motion or an ordered motion.

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Linhart, J. G. "Power from Thermo-Nuclear Reactions," *Nuclear Engng.*, Feb. 1957, 2, 11, p. 60.
Combined U.K.—U.S. Release, *Nature*, Jan. 25, 1958, 181, 4604, pp. 217-233.

2. The Engineering Approach

ZETA, the zero energy thermal apparatus developed at A.E.R.E. and built at Harwell by Metropolitan Vickers, Ltd., consists essentially of a hollow aluminium torus of 3 m mean diameter, with a tube diameter of 1 m, threaded by two cylindrical iron cores carrying the primary turns of what is in essence a simple transformer (Fig. 3). Primary supply is from a bank of 25-kV condensers, total capacity 1,612 μF, capable of storing an energy of 500,000 joules.

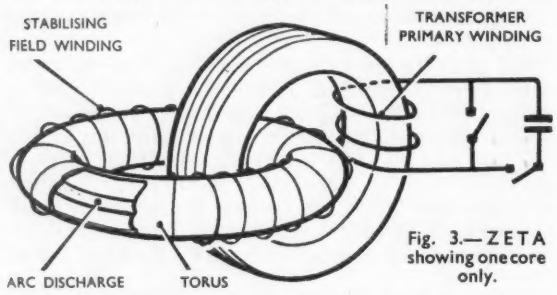


Fig. 3.—ZETA showing one core only.

The stabilizing field—maximum 400 gauss—is generated by coils wound round the torus. The gas contained is substantially deuterium at a pressure around 10^{-4} mm Hg, but has small additions of nitrogen and oxygen; it is made conducting by an RF ionizer. At 10-second intervals the condenser bank can be discharged into the primary circuit, resulting in a stabilized gas discharge lasting several milliseconds. Current pulses of 200,000 amp have been produced and temperatures of 5M°K have been observed. Neutrons have been detected with maximum currents of 84 kA corresponding to a temperature of 2.4M°K, the number produced rising sharply as the temperature increases. The detailed mechanism of neutron production has not been finally established but results are consistent with a thermo-nuclear origin.

A typical single cycle of operations is shown in Fig. 4. When the primary circuit is made, the current rises rapidly to a maximum in the gas, remains substantially constant for an appreciable period and then dies away. The inducing voltage is conveniently expressed as volts/turn as measured by a single loop round the central limb of the ion core. After the initial rise, which for ZETA at its present maximum rating approaches 1.5 kV corresponding to a field in the gas of something over 1 V/cm, the voltage drops and subsequently exhibits sharp transient characteristics. When the voltage initially drops to zero the crowbar switch is thrown which prevents excessive charge reversal on the condensers and extends the current pulse. The generation of neutrons commences at a time corresponding to the approach to maximum current. The discharge pinches at an early point in the cycle and the pinch is stabilized until the current decreases some two milli-seconds after the crowbar action when the filament expands to the walls, at which point it cools rapidly, impurities are introduced and the violent voltage transients occur. These can be suppressed by the addition of 5% nitrogen or neon without affecting the neutron yield.

The Torus

The main torus is constructed of 1-in. aluminium plate, the ring being divided at four places for the insertion of insulating pieces; a continuous tube would, of course, short circuit the transformer. The divisions are diametrically opposite, and two are located in the centre of the ion cores with insulation of polythene and a face-to-face joint whilst in the other pair are bolted insulating viewing sections so that photographic traces and spectrographic measurements can be taken of the discharge. For examination of the interior the tube is raised to atmospheric pressure when the two main halves can be slid apart. Inside the main pressure shell is an aluminium liner consisting of $\frac{1}{4}$-in. overlapping but insulated aluminium rings somewhat in the nature of a lobster shell, there being 48 sections in all. Pumps are provided for evacuating the inner tube and also the space between the liner and the main shell. The liner serves to protect the main shell in which the bulk of the eddy currents is formed and the insulators between the sections from contact with the ionized gas at the end of the discharge and from photo-electric generating radiation which causes breakdown of the insulators. The inner liner is water-cooled to dissipate the 50 kW average heat input into the gas.

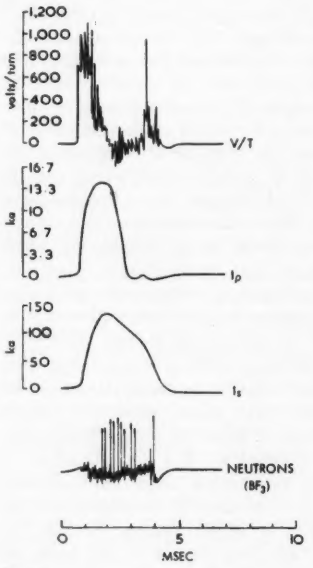
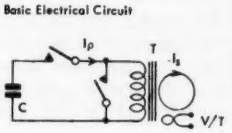


Fig. 4.—Typical operation cycle, showing volts per turn, primary and secondary currents and neutron yield.



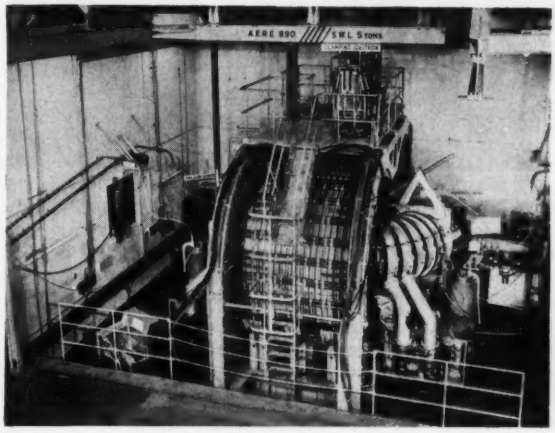
Core

The core consists of two cylindrical units shaped to take the curve of the torus containing a total of 130 tons of grain-orientated silicon iron. Each half consists of 18 coils wound from 4-in. by 0.013-in. iron, individual coils being 10 ft outside diameter, 5 ft inside diameter and weighing a little under 5 tons each. The coils were wound by Telcon Magnetic Cores, Ltd., who were also faced with the problem of transport, as the magnetic properties of such cores can be greatly affected by stresses, induced during moving and by lifting into the vertical plane. Special spiders were constructed and considerable care taken in the design of turning and placing gear and in carrying out these operations. Each coil was annealed by William Beardmore, Ltd., in a specially adapted furnace at 800°C in an atmosphere of nitrogen plus 10% hydrogen. Annealing involves raising the temperature of the coils over a period of 12 hours followed by a soaking for four hours. At Harwell the coils were turned on edge and fixed in a steel frame, being supported by cradles and end rings of Permali densified laminated wood; cable cleats and other members are made of the same material.

Supply Circuit

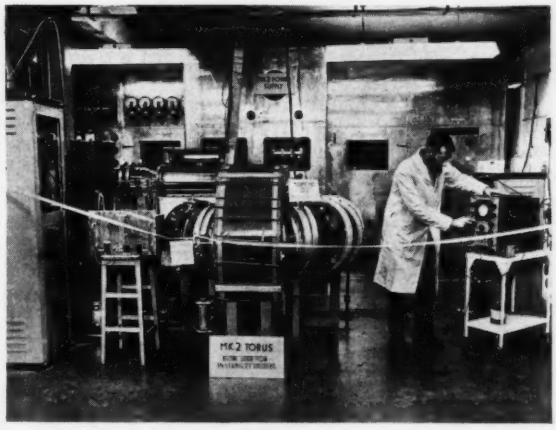
The bank of condensers (the result of two years' development by British Insulated Callender Cables Ltd.) is charged

through a rectifier unit from a mains transformer, to give a total stored energy of 500,000 joules. This voltage is applied to the primary circuit by an air-operated make switch in series with a saturable reactor giving a delay of 500 μsec and a pulse shaping reactor which defines the circuit inductance at 500 μH. The system is safeguarded by an ignitron in series with a resistance of 2 Ω across the primary winding. Mounted on top of the core alongside the Radyne RF generator for the ionization of the gas is the crowbar ignitron, which is caused to operate when the overshoot across the condensers is about 300 V, corresponding to about zero volts per turn on the secondary. The initiating switch operates at 10-sec intervals. To give a maximum flux swing in the iron, the core can be polarized to near saturation in the negative direction.



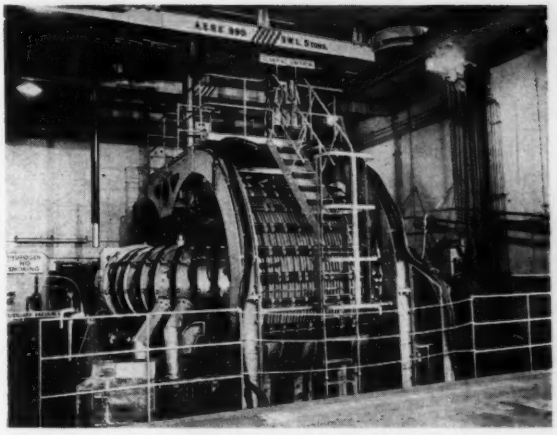
(Above) General view of ZETA.

(Below) The Mark II Torus used for instability studies.



Plasma Measurements

The measurement of the plasma temperature depends upon the Doppler broadening of the emission spectrum of oxygen, added to the deuterium to give a convenient wavelength. Measurements have also been made on nitrogen. The lines are recorded on a Hilger vacuum spectrograph with a dispersion of 20 Å/mm. The breadth of the lines is of the order of 1 Å and a probable accuracy of $\pm 25\%$ in temperature can be achieved. The temperature measured is, of course, the ion temperature, no satisfactory method having been devised for electron temperatures.



(Above) General view of ZETA.

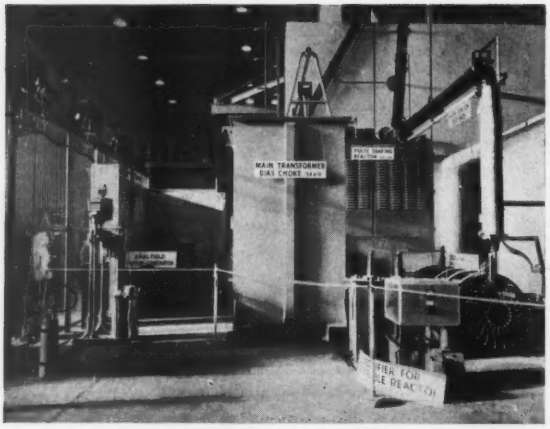
(Below) Control room.

Particle density can be investigated by determination of the absorption of millimeter waves, the absorption in a highly ionized gas being strongly dependent upon the density at a particular frequency. Probes injecting 4 and 8.5 mm waves are inserted into the system, the transmission being measured on the far side of the plasma.

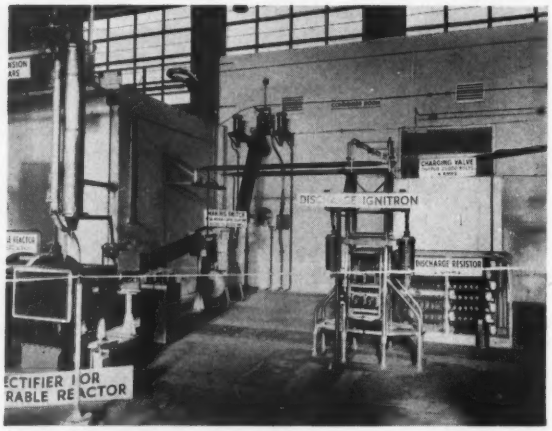
Magnetic flux measurements within the torus provide a great deal of both direct and indirect information, although interpretation of results is not necessarily straightforward.

An extensive system for monitoring and recording voltages, currents, temperatures, etc., has been installed, the main features being an eight-channel recording oscilloscope type SC 36 and a two-channel "Memotron" storage oscilloscope, both developed and manufactured by A. E. Cawkell, Electronic Engineers. The SC 36 embodies eight separate amplifying channels with four 20th Century Electronics double-gun tubes, and is used for photographic and visual work.

The Memotron equipment is believed to be the first of its kind to be used in this country. The Memotron tube incorporates a number of electrodes between its electron guns and the viewing screen. A fine wire "storage mesh" is sprayed with electrons by the "flood gun." The voltage of interest is applied to a conventional deflector-plate system



The HT plant area. (Above) Main transformer bias choke and pulse shaping reactor. (Below) Making switch and discharge ignitron.



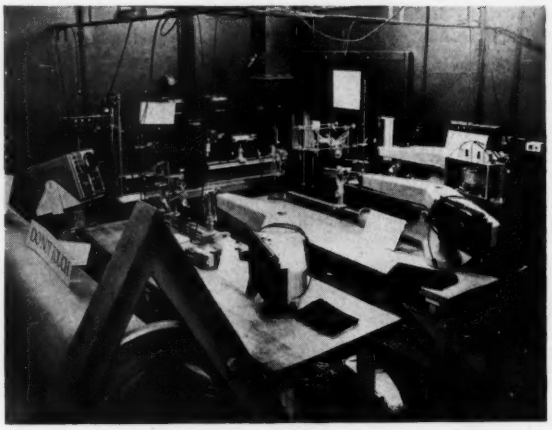
controlling electrons from the "writing gun." Bombardment of the storage mesh by "writing" electrons causes secondary emission, and the bombarded area assumes the same potential as an adjacent positive collector electrode. This area permits passage of flood-gun electrons, which are accelerated to the viewing screen. The storage mesh is either at the "written" (collector) potential, or at the "unwritten" (flood-gun) potential. Electrons from the flood gun continue to pass through the "written" area indefinitely maintaining the picture, until it is erased by a momentary lowering of the collector potential.

One of the most important group of instruments is that concerned with neutron measurement, comprising particle counters and liquid and plastics scintillation counters. Fluxes are at present too low for good counting statistics to be obtained, but it is hoped that in the future it will be possible not only to measure the energy distribution of the neutrons, but correlate this with time. It is anticipated also that at some future time these neutrons will present a health hazard and, for personnel protection, thick concrete surrounds the apparatus; the condenser bank and switchgear and control room are remotely situated, and the usual radiation monitoring apparatus for personnel protection is provided.

SCEPTRE III

The machine developed by the A.E.I. team and built at the research laboratories at Aldermaston, Sceptre III, is

(Below) Spectroscopy laboratory.



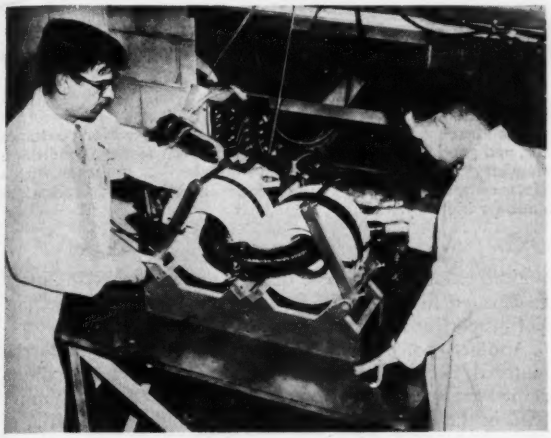
substantially a smaller version of ZETA. The discharge tube is again of aluminium but has an internal diameter of 30 cm and a mean torus diameter of 115 cm. The iron core weighs 4 tons and the primary winding, consisting of about eight turns, is fed from a condenser bank of 150 μF charged to voltages of up to 30 kV. A toroidal (axial) magnetic field of up to 1,000 gauss can be produced within the torus. Apart from overall size, the detailed design of the torus differs somewhat from ZETA and to minimize ion losses the primary winding is wound round the torus rather than round the iron core. The aluminium torus itself has no inner lining and is divided into four main sections by porcelain insulators. The insulators are protected from the discharge by overlapping copper shields.

Currents of up to 200 kA have been generated in the plasma and spectrographic measurements indicate that temperatures of around 3M°K have been achieved. The techniques used for investigating the plasma are similar to those used on ZETA.

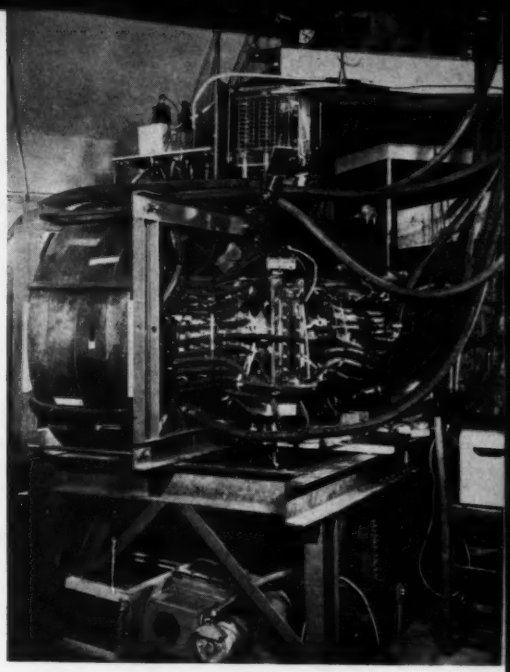
Because of the smaller diameter a greater stabilizing field is required than in ZETA and the generating coils wound round the torus must be water cooled. Dissipating the heat from these coils (165 kW at full power) is one of the limitations of the present design. As with the Harwell apparatus, neutrons have been detected at times corresponding to maximum current in the pulse, although the length of time over which neutrons are emitted is somewhat greater than would be expected on theoretical grounds. The discharge has been stabilized for periods up to 300 μsec; no crowbar switch is installed in the primary circuit and therefore the induced voltage is oscillatory. The number of neutrons generated in the pulse is consistent with a high proportion coming from thermo-nuclear origins, but no definite proof is yet possible.

The Perhapsatron

The majority of experiments in the United States have been made with straight tubes, notably in the devices known as Columbus II and Columbus S-4, but some torus work has been done on the Perhapsatron, built at Los Alamos. The toroid is constructed of glass 0.3 mm thick with a minor diameter of 5.3 cm and a major diameter of 32.4 cm. Energy is fed in from a condenser bank of 225 μF rated at 20 kV with a total connected inductance of 0.08 μH at the torus feed point. The glass walls of the torus are supported and surrounded by a copper sheath split into two halves, horizontally. This has the advantage that the stabilizing field can be pulsed and the heat that



(Right) A general view of SCEPTRE III.



(Left) The "Perhapsatron."

must be dissipated therefore kept down to a reasonable level. Glass has, however, many disadvantages in this type of application and is certainly not suitable for larger machines. The life of the glass ring is believed to be fairly short, but a precision alumina porcelain torus, which is to be delivered shortly, is expected to improve performance.

Currents of up to 230 kA have been generated in the plasma and a stabilized discharge maintained for several microseconds. Neutron emission and magnetic field measurements are consistent with a maximum temperature of around 6M°K, but as no spectrographic measurements can be taken on the apparatus the accuracy of the measurements is difficult to gauge. Taking into account the differences in size of the various machines, and the different maximum input energies, the characteristics of the discharges and the neutron yields of the three toroids discussed are reasonably consistent.

France

It is now known that experiments have been made in France on both linear and toroidal machines and that in the small-minor diameter, nine-feet-torus diameter apparatus, Equator, temperatures in the region of 1M°K have been achieved. The work is being undertaken by Electricité de France in their laboratories at Foutenay-aux-Roses.

Personnel

The initial work on this project was by two independent teams. One, headed by Dr. P. C. Thonemann (reporting to the late Lord Cherwell) at the Clarendon Laboratory, Oxford, was moved, for security reasons, to Harwell in 1951. The other, headed by Dr. A. A. Ware, under Sir George Thomson, at Imperial College, was transferred at the same time to the A.E.I. Research Laboratories at Aldermaston.

The work on ZETA has been done in the General Physics Division at Harwell which is under the direction of Mr. D. W. Fry. The group responsible for the work has been led by Dr. P. C. Thonemann and senior members concerned with ZETA have been Mr. R. Carruthers and Mr. R. S. Pease, with Mr. J. T. D. Mitchell of the Engineering Division, and Dr. W. B. Thompson of the Theoretical Physics Division.

At the A.E.I. Research Laboratories, directed by Dr. E. E. Allibone, the work on Sceptre has been continued by Dr. Ware, with a team under Mr. D. R. Chick of the Nuclear Physics Section.

Main and Sub-contractors for Zeta

METROPOLITAN-VICKERS ELECTRICAL CO. LTD., Trafford Park, Manchester, 17.
Main contractors and collaborators in the design.

TELCON MAGNETIC CORES LTD., Chapelhall Industrial Estate, Chapelhall, Lanarkshire.
Development of ring-type cores.

BRITISH INSULATED CALLENDERS CABLES LTD., 21 Bloomsbury Street, London, W.C.1.
Development of main 25 kV capacitors.

WM. BEARDMORE AND CO. LTD., Parkhead Steelworks, Glasgow.
Heat treatment of ring cores.

BRENTFORD TRANSFORMERS LTD., Crawley, Sussex.
Transformers.

THE BRITISH THOMSON-HOUSTON CO. LTD., Rugby, Warwickshire.
Ignitron equipment.

A. E. CAWKELL (ELECTRONIC ENGINEERS), 6-8 Victory Arcade, Southall, Middx.
Main measuring and monitoring equipment.

W. E. CHIVERS AND SONS LTD., Devizes, Wilts.
Civil engineering and building work.

DYNAMO AND MOTOR REPAIRS LTD., Wembley Park Works, North End Road, Wemb'ey, Middx.
Motor-generator set.

EDISON SWAN ELECTRICAL CO. LTD., 155 Charing Cross Road, London, W.C.2.
Cables.

ENGLISH ELECTRIC CO. LTD., Marconi House, Strand, London, W.C.2.
Switchgear.

GEO. ELLISON LTD., Ellison House, Highfield Road, Edgbaston, Birmingham, 15.
Isolators.

HILGER AND WATTS LTD., Hilger Division, 98 St. Pancras Way, Camden Road, London, N.W.1.
Spectrograph equipment for temperature measurement.

GEO. KING LTD., Argyle Works, Stevenage, Herts.
Cranes and hoists.

LEE AND WILKES LTD., Priory Works, Brewery Street, Birmingham, 6.
Copper tubes.

MARTONAIR LTD., Parkshot, Richmond, Surrey.
Air operating cylinders.

NAGARD LTD., 18 Avenue Road, Belmont, Surrey.
Oscilloscopes.

PERMALI LTD., Gloucester.
Insulating cheeks and supports for the main transformer winding.

RADIO HEATERS LTD., Wokingham, Berks.
Radyne apparatus for ionization of the gas in the toroid.

SOLUS-SCHALL LTD., 15-18 Clipstone Street, Gt. Portland Street, London, W.1.
Health monitor equipment.

STANDARD TELEPHONES AND CABLES LTD., 10 Essex Street, London, W.C.2.
Rectifier equipment.

20TH CENTURY ELECTRONICS LTD., Centronics Works, King Henry's Drive, New Addington, Croydon, Surrey.
Barium trifluoride neutron counters.

WESTINGHOUSE BRAKE AND SIGNAL CO. LTD., 82 York Way, King's Cross, London, N.1.
Rectifier equipment.

ZIRCONIUM—

Reasons for the interest in zirconium as a reactor core material include low neutron absorption cross-section (when free from hafnium impurity), excellent corrosion resistance in high-temperature water, and good fabricability under controlled atmosphere conditions. The paper summarizes metallurgical, physical, chemical and nuclear data together with a brief discussion on the effects of irradiation on the properties of zirconium, and applications of the metal outside the nuclear industry.

IN nuclear reactors intended for power production neutron economy is of paramount importance, and potential uses of zirconium become apparent when its properties are compared with the other metals of low neutron absorption cross-section.

There are basically four metals which can be used in the core of a thermal reactor using natural uranium fuel: beryllium, magnesium, aluminium and zirconium. Beryllium, the most attractive metal from the nuclear standpoint is still scarce and expensive, has limited ductility and requires specialized fabrication techniques. Magnesium and aluminium are used as canning materials in British gas-cooled reactors, but cannot be used as stress-bearing members in future reactors of this type operating at higher temperatures, owing to poor creep properties and comparatively low melting points. Neither material is suitable for use in pressurized water reactors, because of poor corrosion resistance.

Zirconium and its alloys, despite high melting points, also show rather poor high-temperature mechanical properties, but alloys with a satisfactory oxidation resistance and mechanical properties at 500°C could be rapidly developed for advanced gas-cooled reactors. The main application of zirconium to date has been in pressurized water reactors built in the U.S. Pure zirconium is the only metal of low cross-section which is corrosion-resistant to pressurized water at temperatures around 300°C. It was used as fuel cladding in the STR Mark I core. The corrosion resistance of zirconium depends critically upon certain impurities, notably nitrogen, and an improved alloy known as Zircaloy 2, with superior corrosion resistance to high - temperature water, and greater strength, was developed by American workers for the Mark II core of STR.

Sodium - cooled graphite-moderated reactor systems have been proposed in which the fuel is canned in zirconium or stainless steel, which consequently is in contact with high-temperature molten sodium. Under these conditions the rate of corrosion of zirconium depends critically upon the oxygen content of the sodium, and this has to be kept at as low a level as possible by hot trapping. This is important, because oxygen from the zirconium oxide film tends to dissolve in the underlying metal at elevated temperatures, causing deterioration in mechanical properties.

Another potential use for zirconium is as a barrier material between coolant and moderator in a sodium-cooled graphite-moderated reactor.[1] Here the zirconium is used in the form of liner tubes in a graphite calandria, or alternatively the graphite core consists of an assembly of hexagonal columnar cells clad with thin zirconium sheet.

Finally, an important use of zirconium is as an alloy addition to uranium to increase the bulk and heat transfer surface, and to improve the corrosion properties of the fuel in reactors using highly enriched uranium. Such alloying should improve the dimensional stability of the fuel under irradiation, and remove susceptibility to hydrogen embrittlement and cracking encountered with other alloy fuels exposed in high-temperature water.

Although classified until recently as a rare metal, zirconium actually constitutes a greater percentage of the earth's crust than some of the commoner metals such as copper and lead. The principal minerals are zircon ($ZrSiO_4$) and baddeleyite (ZrO_2). The zirconium minerals always contain some percentage of hafnium.

In the commercial process for converting zircon to zirconium metal, zircon sand is reacted with charcoal or

TABLE 1

Processes for the Separation of Hafnium from Zirconium (2)

Type of process	Compounds used	Remarks
Fractional crystallization.	(1) Double fluorides K_2MF_6. (2) Oxyhalides $MOBr_2$ or $MOCl_2$. (3) Ammonium double oxalates.	The salt must contain Hf or Zr in the anion, owing to the hydrolysability of salts containing Hf or Zr cations.
Fractional precipitation.	(1) Phosphate precipitation. (2) Ferrocyanide precipitation. (3) Hydroxide separation. (4) Arsenate separation. (5) Peroxide precipitation. (6) Organic acids (benzoic, tartaric, etc.).	Methods are faster than fractional crystallization but less economical.
Fusion methods.	Fusion of pyrophosphates followed by leaching with Hf, and insoluble residue separated.	The insoluble residue contains up to 50% Hf.
Distillation separations.	(1) Sublimation of mixed tetrachlorides. (2) Fractionation of double chlorides $2MCl_4 . 2PCl_5$ and $3MCl_4 . 2POCl_3$.	Product obtained cannot readily be reconverted to tetrachloride for the Knoll process.
Ion exchange.	(1) Cation exchange: elution of zirconyl and hafnyl chloride adsorbed on Dowex 50 with 6M HCl. (2) Anion exchange: elution of fluoride complex anions adsorbed on Dowex 1 with 0.5M Hf+ 1.0M HCl mixture.	Both cation and anion exchange have been used, as hafnium and zirconium hydrolyse into several cation species, and form complex anions.
Adsorption separations.	(1) Cellulose column. Zirconyl and hafnyl nitrate adsorbed into filter pulp and eluted with nitric acid-ether mixture. Hf retained on column. (2) Silica gel column. Anhydrous hafnium tetrachloride in methanol is selectively adsorbed on activated silica gel.	Process is unattractive commercially due to ignition and explosion risks.
Solvent extraction separations.	(1) Tributyl phosphate method. Zirconium is extracted into TBP from impure zirconyl chloride and nitrate solutions. (2) Thenoyl-tri-fluoroacetone separation. TTA forms chelate compounds with Zr and Hf which are differentially soluble in organic solvents. (3) Thiocyanate separation. Separation of Hf and Zr, and the preparation of pure Hf is possible by a solvent extraction method in which an aq. soln. of the sulphates is shaken with an ether solution of thiocyanic acid. The hafnium is preferentially extracted into the organic layer.	Product containing less than 50 ppm Hf can be obtained by this process. Process is efficient for Hf separations. Ether may be conveniently replaced by hexone, which is cheaper.

and its Alloys

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coke in an arc furnace to form carbide or carbonitride, which is subsequently chlorinated to form impure zirconium tetrachloride. Subsequent to this a Kroll process is used.

One of the most important stages in the preparation of zirconium for nuclear purposes is the removal of hafnium which has an unacceptably high neutron absorption cross-section. Many techniques have been applied to this problem including ion exchange and solvent extraction. The main processes are summarized in Table 1.

Consolidation of zirconium sponge or iodide wire to billet form is a necessary intermediate step before fabrication techniques can be applied. This is done generally by induction or arc melting using either consumable or non-consumable electrode techniques.[2] By 1953 the U.S. had developed equipment for producing 12-in. 500-lb. ingots.

Physical Properties

The physical and metallurgical properties of zirconium are extremely sensitive to impurity content. For example, the melting point of zirconium is raised by each of the three most important non-metallic contaminants, oxygen, nitrogen and carbon. Pure zirconium undergoes a phase transformation at $862 \pm 2°C$; the low-temperature alpha phase having a close-packed hexagonal structure with axial ratio slightly less than that required for ideal close packing. The high-temperature beta phase is body-centred cubic, with unit cell parameters $a = 3.61$ Å at 900°C.[3] The variation of lattice parameters with temperatures up to 600°C has been determined by Russell[4, 5] and is shown in Fig. 1. The sharpness of the phase transition is affected by the presence of oxygen, nitrogen or hydrogen in the metal, and in general the transformation temperature is raised by these elements and by aluminium, tin and hafnium. Most other metals lower the transformation temperature.

Russell has used X-ray techniques to determine the true linear expansion coefficients for alpha zirconium containing less than 50 p.p.m. hafnium, and also for metal containing 1.2 atomic per cent hafnium. Measurements were extended up to 600°C, and to below the Curie temperature which is estimated to be approximately 280°K.[4, 5, 6] The results are shown in Figs. 2 and 3. McGeary[7] has shown by dilatometric techniques that a contraction occurs on heating zirconium through the alpha-beta transformation. This is thought to arise from a decrease in atomic size in going from a structure with co-ordination number 12 (close-packed hexagon) to one with co-ordination number 8 (body-centred cubic). The transformation relationships between the two phases were

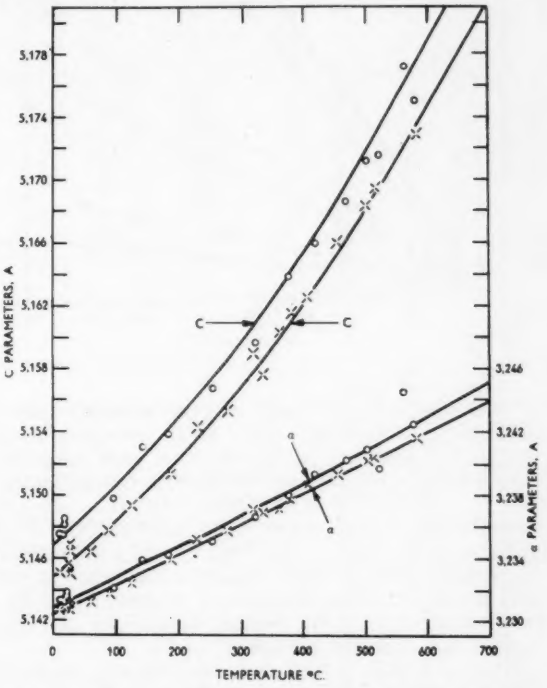


Fig. 1.—Lattice parameters for zirconium containing less than 0.005 at. % and 1.2 at. % hafnium, with temperature (4, 5).

determined in 1934 by Burgers[8] in a classical paper, as

$$(0001)\ \alpha \parallel (110)\ \beta \text{ and } (11\bar{2}0)\ \alpha \parallel (111)\ \beta.$$

McGeary and Lustman[9] related anisotropy of thermal expansion with metal texture, and were able to correlate the widely diverse results of other investigators in terms of different preferred orientation.

The thermal conductivity of zirconium compares

TABLE 2

Tensile Properties of Commercial Arc Melted Zirconium Containing 2% Hafnium

Specimen No.	Initial hardness (VHN)	Temperature (°C)	Limit of proportionality (ton/in²)	Ultimate tensile strength (ton/in²)	Elongation (%)	Reduction of area (%)
		Extruded condition (average grain size 0.015 mm)				
LY.41*	171‡	R.T.	24.0†	34.0	30	52
LY.43	171	200	10.4	19.6	45	67
LY.45	173	400	7.0	12.1	40	80
LY.47	173	500	6.3	9.4	72	92
		Annealed (700°C for 20 h) condition (average grain size 0.050 mm)				
LY.40	165	R.T.	26.0	32.0	27	41
LY.42	166	200	13.0	17.6	35	52
LY.44	166	400	5.8	9.4	47	83
LY.46	168	500	5.4	8.2	33	84

* LY. numbers were from billet with the following analysis :
Oxygen 0.23% : Nitrogen 0.016% : Hydrogen 0.003% : Carbon 0.05%.

† It should be noted that the limits of proportionality included in the tensile data were obtained from tensile curves plotted on the Hounsfield charts at × 16 magnification. From comparisons with high sensitivity test data, the quoted values appear to correspond approximately to 0.5% Proof Stress, being 4 to 6 times greater than the limits of proportionality measured by the more sensitive means.

‡ The hardness measurements were made on sections perpendicular to the extrusion or rolling direction.

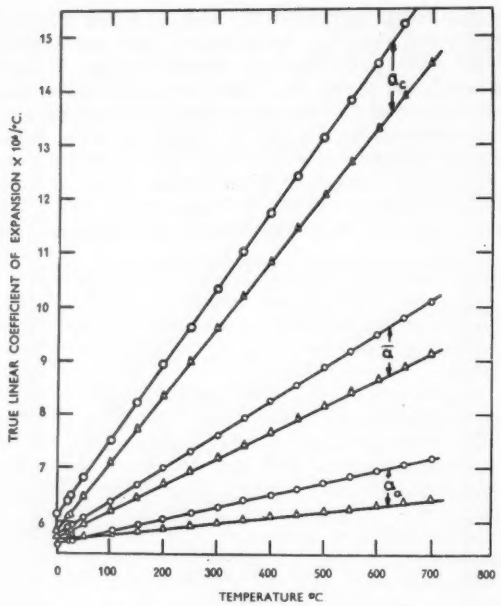
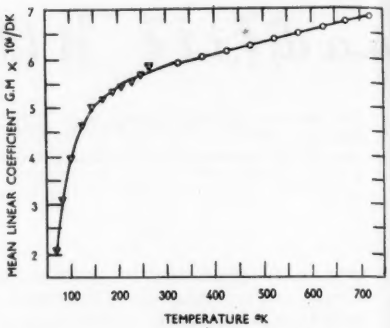


Fig. 2.—(Left) True linear expansion coefficients for α-zirconium with (O) less than 0.005 at. % and (Δ) 1.2 at. % hafnium with temperature.

Fig. 3—.(Right) Mean linear coefficients of expansion for zirconium containing 1.2 at. % hafnium, as a function of temperature (O Russell Δ Erfling) (68).



unfavourably with that of other canning materials such as beryllium or aluminium. Bing[10] et al. have determined thermal and electrical conductivities of pure zirconium and some alloys, and have derived the empirical relationship

$$K=0.0308\ (\sigma-0.00327)T+0.0381$$

where K is thermal conductivity (watt/cm-°C), σ is electrical conductivity $(\mu\text{ohms-cm})^{-1}$ and T is absolute temperature. With a known value for the resistivity ρ of zirconium at 273°C and the Lorentz constant L, the electronic component of the thermal conductivity (K_e) may be calculated from the relation $K_e=LT/\rho$.

This gives a value of 0.167 ± 0.01 watt/cm, deg. compared with a value of 0.215 watt/cm, deg. derived by direct experiment. It is assumed that the difference 0.05 watt/cm, deg. gives the value for the lattice conduction. This component is always found to decrease with increasing temperature ($\propto T^{-n}$ where n is between 1 and 2) while the electronic component may be assumed to be constant in the range where $d\rho/dT$ is linear. This explanation must be invoked to account for the observed decrease in thermal conductivity of pure zirconium with increasing temperature[11] in the range 0-300°C.

The electrical resistivity of zirconium is a function of its purity and its metallurgical condition. The effect of oxygen content on resistivity of iodide zirconium was studied systematically by Treco[12] and is summarized in Fig. 4. The results have been extrapolated to give a resistivity for metal of zero oxygen content.

Cook[13] et al. have investigated the electrical resistivity of zirconium as a function of temperature, and found that there was a linear relationship from −186°C to +200°C. Above 200°C the resistivity-temperature slope decreases, and the resistivity approaches a maximum near the alpha-beta transformation temperature. It then drops to a minimum between 875°C and 950°C, and rises with constant slope to 1,400°C. This is not understood.

In a study[13] of the effect of cold work on resistivity it was found that swaging to a reduction in area of 84% increased the resistivity by 4 to 6%, but had no effect on the slope of the resistivity-temperature curve near room temperature.

Mechanical Properties

A wide range of yield strengths ranging from 8,000 to 15,000 lb/in.² and tensile strengths ranging from 25,000 to 40,000 lb/in.² has been reported in the literature[2] for pure annealed zirconium. It is thought that the variation is due to gas contamination during melting and fabrication procedures, and also, possibly, due to insufficient annealing. Hot rolling of zirconium, followed by different annealing

TABLE 3

Tensile Properties of Commercial Arc Melted Low Hafnium (< 300 ppm) Zirconium

Specimen No.	Initial hardness (VHN)	Initial grain size (mm)	Temperature (°C)	Limit of proportionality (ton/in²)	Ultimate tensile strength (ton/in²)	Elongation (4 A√G.L) (%)	Reduction of area (%)
Hot-rolled							
PJH.13*	164	0.026	20	22.5	31.5	26	44
PJH.14	164	0.026	200	14.2	20.3	30	55
PJH.15	163	0.028	400	10.8	14.2	24	73
PJH.16	163	0.028	500	7.2	9.5	48	91
PJG.1	158	0.029	600	2.33	3.03	52	>99
PJG.3	158	0.029	700	1.35	1.59	50	>99
Annealed 750° for 30 min							
PJH.1	140	0.030	20	12.8	27.2	30	42
PJH.2	140	0.030	100	10.6	22.9	35	46
PJH.3	139	0.032	200	7.7	14.7	46	56
PJH.4	139	0.032	300	4.8	10.5	40	72
PJH.5	142	0.039	400	3.6	9.2	34	76
PJH.12	144	0.034	450	4.7	7.9	33	81
PJH.6	142	0.039	500	3.49	7.1	46	91
PJH.7	138	0.031	600	1.89	3.32	104	>99
PJH.11	144	0.034	700	0.89	1.39	59	>99
PJH.8	138	0.031	800	0.60	0.81	69	>99
PJH.9	136	0.030	900	0.22	0.28	44†	>99

* PJ. numberz were from billet with the following analysis:
Oxygen 0.13% : Nitrogen 0.008% : Hydrogen 0.0033%.
† Leak developed in vacuum system during straining which may have caused specimen to be contaminated.

Nuclear Engineering
DATA SHEET
No. 6. Zirconium

A. PHYSICAL PROPERTIES

TABLE A1
Lattice Parameters and Specific Gravity of Zirconium as a Function of Hafnium and Oxygen Content (2)

Composition		Lattice constant (kx units)		Vol. increase through O_2 absorption (%)		Specific gravity	
Hf (at %)	O_2 (at %)	a	c	Experimental	Calculated from lattice constants	Experimental	Calculated from lattice constants
			De Boer and Fast (39) Annealed 1,650°C				
0.5	0	3.22$_5$	5.13$_4$			6.540	6.541
0.5	2			0.1$_5$		6.555	
0.45	10	3.23$_6$	5.15$_1$	1.0$_5$	1.0	6.600	6.601
0.4	29	3.23$_6$	5.17$_0$		1.4		6.733
0.4	21.5			1.5		6.755	
0.35	30	3.23$_6$	5.19$_1$		1.8		6.906
			Treco (40)				
0.0147$_2$	0.147	3.2256$_2$	5.1370$_9$				6.506
0.0142	0.866	3.2269$_5$	5.1387$_6$				6.507
0.0142	2.02	3.2290$_3$	5.1424$_6$				6.507
			Rostoker (41) Annealed 1,000°C				
0.02	5.45	3.239	5.157				6.490
0.02	10.45	3.238	5.160				6.559
0.02	15.00	3.244	5.167				6.565
0.02	21.15	3.246	5.171				6.621
0.02	30	3.240	5.187†				6.724
			Russell (6)				
<0.005	0.073	3.2311$_5$	5.1475$_6$	(c/a 1.5931$_6$)			6.490
1.2	0.073	3.2307$_6$	5.1455$_1$	(c/a 1.5926$_3$)			6.566

† Two-phase alloy.

Variation of Lattice Parameters with Temperature (6)

Low Hf (<0.005 at %) and low oxygen (0.073 at %) iodide zirconium.
$c = 5.14105 + 1.1532\times10^{-5}\,T + 3.6416\times10^{-9}\,T^2$.
$a = 3.22612 + 1.6072\times10^{-5}\,T + 3.6940\times10^{-9}\,T^2$.

High Hf (1.2 at %) and low oxygen (0.073 at %) iodide zirconium.
$c = 5.13909 + 1.2470\times10^{-5}\,T - 3.2209\times10^{-9}\,T^2$.
$a = 3.22554 + 1.7337\times10^{-5}\,T + 1.7631\times10^{-9}\,T^2$.

Molecular Volume (6)

Low Hf iodide zirconium as above .. .. .. 14.02 cm³/mole.
High Hf iodide zirconium as above .. .. .. 14.01 cm³/mole.

TABLE A2
Coefficients of Expansion (6)

	<0.005 at.% Hf	1.2 at.% Hf
True instantaneous linear coefficients of expansion/°C		
α_c ∥ c axis	6.39×10^{-6}	6.09×10^{-6}
α_a ⊥ c axis	5.64×10^{-6}	5.69×10^{-6}
True linear for random orientation $\bar{\alpha}$/°C	5.89×10^{-6}	5.82×10^{-6}
True volume $\alpha_v = 3\bar{\alpha}$/°C	17.68×10^{-6}	17.47×10^{-6}
$\alpha_c\left(\frac{1}{c}\frac{dc}{dT}\right)$	$(6.106+0.01358\,t)\times10^{-6}$/°C	$(5.844+0.01237\,t)\times10^{-6}$/°C
$\alpha_a\left(\frac{1}{a}\frac{da}{dt}\right)$	$(5.599+0.002241\,t)\times10^{-6}$/°C	$(5.665+0.001053\,t)\times10^{-6}$/°C
Isotropic point ($\alpha_c=\alpha_a$) 236.4°K at $\alpha_c=\alpha_a=5.592\times10^{-6}$/°C		

Transition Temperatures
Melting point, 1,852±10°C (Grade 3 crystal bar) (42).
Boiling point, ~3,580°C (43).
Transformation point, 862°C (44).

Thermal Conductivity values are given in the text.

Specific Heat
C_p (25°C) 0.0659 cal/g °C (45)
for zirconium containing 0.025 at.% Hf, 0.67 at.% Fe, 0.15 at.% C, 0.026 at.% N.
Specific heat in the low-temperature range 1.8 to 4.2°K for 99.5% Zr is given by equation $C_v = 6.92\times10^{-4}\,T + 464.5\left(\frac{T}{265}\right)^3$ cal/mole deg.
The first term is the electronic contribution, and the second is the lattice contribution (46).

TABLE A3
Heat Capacity and Derived Thermodynamic Functions for Zirconium at Various T

Temp. °K	$C_p°$ cal/mole deg.	$S°$ cal/mole deg.	$H°-H_0°$ cal/mole deg.	$(H°-H_0°)/T$ cal/mole deg.
14	0.090	0.030	0.31	0.022
25	0.489	0.169	3.61	0.126
50	2.212	1.016	36	0.720
75	3.609	2.200	110.2	1.469
100	4.460	3.362	211.7	2.117
125	4.986	4.421	330.5	2.664
150	5.299	5.359	459.3	3.062
175	5.525	6.193	594.8	3.399
200	5.691	6.942	735.1	3.675
225	5.824	7.621	879.1	3.907
250	5.918	8.240	1,025.6	4.103
275	5.981	8.807	1,174.5	4.271
298.16	6.012	9.292	1,313.3	4.405
300	6.014	9.329	1,324.4	4.415

The molar heat capacity of zirconium (47) as a function of t
1,200°C is given by the equations:—
Zr_α: $C_p = 6.83 + 1.12\times10^{-3}\,T - 0.87\times10^{5}\,T^{-2}$ (298 to 1,135°K
Zr_β: $C_p = 7.27$ (1,135 to 1,400 K). T in degrees absolute.

Heat Content
The heat content as a function of temperature between 400 an
by the equation (47)
Zr_α $H_T° - H_{298}° = 6.83\,T + 0.56\times10^{-3}\,T^2 + 0.87\times10^{5}\,T^{-1} - 2378$ (2
Heat of Fusion ~5.5 kcal/mole (43).
Heat of Vaporization $\Delta H_0° = 142{,}150 \pm 350$ cal/mole (48).
Heat of Transformation ~920 cal/mole (47).

TABLE A4
Entropy and Free Energy

Temp. °K	$S_T° - S_{298}°$ cal/mole, °K	−(F cal
400	1.91	
500	3.44	
600	4.74	
700	5.88	
800	6.88	
900	7.78	
1,000	8.60	
1,100	9.36	
1,135 (α)	9.61	
1,135 (β)	10.42	
1,200	10.82	
1,300	11.40	
1,400	11.94	

Vapour Pressure
$\log p\ (\text{at}) = \frac{-31{,}066}{T} + 7.3351 - 2.415\times10^{-4}\,T$ (1,949 to 2,05
conium containing 0.99 at % Hf, 0.05 at % W and 0.37 at % othe

TABLE A5
Electrical Resistivity (49)

Zirconium grade	Resistivit
High-purity crystal bar	44
"Regular" crystal bar machined ..	45
Mg-reduced, melted, machined	54
Mg-reduced, melted, cold-drawn wire ..	52
Mg-reduced, melted, annealed wire ..	50
Less pure Mg-reduced, cold-drawn wire..	60

Resistivity figures for Hf-free iodide zirconium have been reporte
Electrical resistivity at 0°C (μohm, cm) .. .. ..
Temperature coefficient of electrical resistance ($\alpha\times10^4$/°C)
Temperature of maximum resistance (°K) .. .. ..
Temperature of minimum resistance (°K) .. .. ..
Maximum resistance (μohm, cm) .. .. ..
Minimum resistance (μohm, cm) .. ..

* Specimen possibly contaminated with oxygen.

TABLE A6
Effect of Cold Work on the Electrical Resistance of

Condition	Density	Tu D Mi har
Annealed 1 h at 650°C after cold swaging from 0.95 in. to 3/16 in. with no intermediate anneal	6.505±0.001	10
Cold-swaged from 0.95 in. to 5/16 in. annealed at 650°C, further cold-swaged to 3/16 in. (64% cold reduction)	6.505±0.001	17
Cold-swaged from 0.95 in. to 3/16 in. with no intermediate anneal (96% cold reduction)	6.50±0.001	19

* Values represent the average of a minimum of 25 specir
Material analysed 0.04% Hf; 0.02% Fe; 0.04%C

A3
ns for Zirconium at Various Temperatures (45)

$H°-H_0°$ al/mole deg.	$(H°-H_0°)/T$ cal/mole deg.	$-(F°-H_0°)/T$ cal/mole deg.
0.31	0.022	0.008
3.61	0.126	0.043
36	0.720	0.296
110.2	1.469	0.730
211.7	2.117	1.245
330.5	2.664	1.776
459.3	3.062	2.297
594.8	3.399	2.795
735.1	3.675	3.267
879.1	3.907	3.714
1,025.6	4.103	4.137
1,174.5	4.271	4.536
1,313.3	4.405	4.887
1,324.4	4.415	4.914

zirconium (47) as a function of temperature up to
tions:—
^{3} $T-0.87\times10^3\,T^{-2}$ (298 to 1,135°K).
400°K). T in degrees absolute.

on of temperature between 400 and 1,400°K is given
$5\times10^{-3}\,T^2+0.87\times10^3\,T^{-1}-2378$ (298 to 1,135°K).
/mole (43).
$H_0°=142{,}150\pm350$ cal/mole (48).
~920 cal/mole (47).

TABLE A4
tropy and Free Energy

$S_T°-S_{298°}$ cal/mole, °K	$-(F_T°-H_{298°})/T$ cal/mole, °K
1.91	9.53
3.44	10.02
4.74	10.58
5.88	11.16
6.88	11.72
7.78	12.28
8.60	12.78
9.36	13.28
9.61	13.45
10.42	13.45
10.82	13.80
11.40	14.30
11.94	14.48

$51-2.415\times10^{-4}\,T$ (1,949 to 2,054°K) (48) for zir-
Hf, 0.05 at % W and 0.37 at % other impurities.

TABLE A5
ectrical Resistivity (49)

de	Resistivity (μohm, cm)
.. .. ..	44.1
hined ..	45
ned ..	54
rawn wire ..	52.5
led wire ..	50.5
l-drawn wire..	60

odide zirconium have been reported (50):—

(μohm, cm)	41
electrical resistance ($\alpha\times10^4$/°C) ..	44
esistance (°K)	1,150*
esistance (°K)	1,430*
m, cm)	144*
m, cm)	126*

possibly contaminated with oxygen.

TABLE A6
n the Electrical Resistance of Crystal Bar Zirconium (49)

	Density	Tukon DPH Micro-hardness	Electrical Resistivity* μohm, cm	
			25°C	−195.8°C
waging from ntermediate	6.505±0.001	104±3	43.74±0.08	7.14±0.03
in. annealed to 3/16 in.	6.505±0.001	179±6	44.63±0.16	
in. with no reduction)	6.50±0.001	191±4	44.67±0.09	8.05±0.03

e average of a minimum of 25 specimens for each condition.
lysed 0.04% Hf; 0.02% Fe; 0.04%C and 0.002% N.

TABLE A7
Resistivity of High-purity Zirconium (51)

Temp. (°K)	ρ (μohm, cm)
295.7	45.6
73.3	8.68
4.2	2.14

TABLE A9
Effect of Cold Work and Annealing on the Temperature Coefficient of Resistance of Zirconium (52)

Treatment	$\alpha\times10^4$
Crystal bar	43.7
Unannealed swaged wire	38.7
Same after six months at R.T.	39.2
400°C for 3 h	40.5
500°C for 3 h	41.9
600°C for 1 h	42.0
700°C for 1 h	41.6
800°C for 1 h	41.2
900°C for 1 h	41.6
1,000°C for 1 h	41.8
1,000°C for 15 min	42.2

Thermoelectric Force
The thermoelectric power for Grade 2 zirconium crystal bar versus constantan and alumel was found to obey the relations given below, from 0 to 600 C (55).

$$\text{Zirconium-constantan: } \frac{dE}{dt}=0.05725-109.4\,t\times10^{-6}\ \text{mV/°C}.$$

$$\text{Zirconium-alumel: } \frac{dE}{dt}=0.02881-336\,t\times10^{-7}\ \text{mV/°C}.$$

Superconductivity
Superconductivity has been observed in zirconium at 0.68°K (54).

Variation

Hafnium at %
100
97.5
62
51
0.5
0

Effect of Pres

* Transition

Electrochemical E
Normal valency e
is 0.2363 mg/coulom

Magnetic Suscept
Molar susceptibili

Hall Effect
Hall coefficient
$+11.8\times10^{-13}$ V, cm

B. MECHANICAL PROPERTIES

Elastic Constants
There are no data available on zirconium single crystals.
A determination of Young's Modulus in various directions in the plane of cold-rolled sheet made from sponge base zirconium (U.S. Bureau of Mines) gave the following values:—

0 degrees to the rolling direction: 13.9×10^6 lb/in.^{2} (57)
45 degrees to the rolling direction: 13.6×10^6 lb/in.^{2}
90 degrees to the rolling direction: 14.0×10^6 lb/in.^{2}

The best room temperature value of Young's Modulus for pure annealed zirconium is 13.7×10^6 lb/in.^{2} (58).
The variation of Young's Modulus with temperature was determined by a vibrational method, and is shown in Fig. 14 (58).

Elastic shear mod
Poisson's ratio

Compressibility w

Tensile Properties have been summarized in Tables 2 to 8 and in Figures 5 to 7.

Creep Properties have been summarized in Tables 9 to 11 and in Figures 8 and 9.

TABLE B2
Fatigue Properties of Zirconium and Some Al

Materials	Test Temp. (°C)	Tensile Strength (lb/in.^{2})	Fatigue Lim (lb/in.^{2}) Unnotched Flexure	N
Unalloyed Iodide Zr	R.T.	33,300	21,000	
Unalloyed Iodide Zr	400	12,800	10,500	
Iodide Zr .. .. +0.34 wt. % O_2	R.T.	93,700	56,000	1
Iodide Zr .. .. +0.34 wt. % O_2	400	22,400	15,000	
Iodide Zr .. .. +2.0 to 2.2 wt. % Sn	400	21,100	18,000	
Iodide Zr .. .. +2.1 to 2.7 wt. % Sn	400	21,800	20,000	
Sponge Zr .. .. +2.5 wt. % Sn+0.14% O_2	400	31,500	24,000	
			Axial load	
Iodide Zr .. .. +2.5 wt. % Sn	260	27,600	21,500	1

* The strength reduction factor K_f = unnotched fatigue strength,

TABLE B3
Effect of Heat Treatment on the Hardness of Zirconium

Material	Heat-treatment (°C)
Arc-melted Iodide Zr	Hot-rolled at 790° (α range) and slow coole
	Soaked 1 h at 900° (β range) and water-que
	Soaked 1 h at 1,000° and water-quenched
	Annealed 1 h at 1,000° and water-quenched
	Annealed 20 h at 750° .. .. ..
Induction-melted Iodide Zr+0.9 wt.% Molybdenum	Hot-rolled at 1,000° and air-cooled ..
	Soaked 1 h at 700° and slow-cooled ..
	Soaked 1 h at 950° and water-quenched

TABLE A8

Variation of Temperature Coefficient of Resistance in Zirconium-Hafnium Alloys (50)

Hafnium at %	Zirconium at %	$\alpha \times 10^4$
100	0	44.0
97.5	2.5	38.7
62	38	36.0
51	49	35.5
0.5	99.5	43.5
0	100	44.0

α is defined as $\frac{\rho(100^\circ C) - \rho(0^\circ C)}{100\rho(0^\circ C)}$

TABLE A10

Effect of Pressure on the Electrical Resistivity of Zirconium (53)

Pressure (kg/cm²)	R (at Pressure) / R (at Zero Pressure)
0	1.0000
10,000	0.9977
20,000	0.9954
30,000	0.9933
40,000	0.9914
50,000	0.9894
60,000	0.9874
70,000	0.9856
80,000	0.9836
90,000	*

* Transition above 80,000 kg/cm² with 16–17% drop in resistance.

ctrochemical Equivalent

ormal valency of Zr is 4, and the corresponding electrochemical equivalent 2363 mg/coulomb.

gnetic Susceptibility

olar susceptibility of zirconium at room temperature: 120×10^{-6} c.g.s. units.

l Effect

all coefficient for high-purity crystal bar zirconium was determined as $.8 \times 10^{-13}$ V, cm/amp, gauss (56).

OPERTIES

TABLE B1

	Crystal Bar	Bureau of Mines Metal
lastic shear modulus .. } (59)	4.76×10^4	5.24×10^6 lb/in.²
oisson's ratio .. .. }	0.33	0.35

ompressibility was found to be governed by the equations, up to 12,000 kg/cm²:

$$-\frac{\Delta v}{v} = 10.97 \times 10^{-7} p - 7.44 \times 10^{-12} p^2 \text{ at } 30^\circ C.$$

$$-\frac{\Delta v}{v} = 11.06 \times 10^{-7} p - 7.80 \times 10^{-12} p^2 \text{ at } 70^\circ C.$$

p is the pressure in kg/cm² (60).

32

and Some Alloys (61) (62)

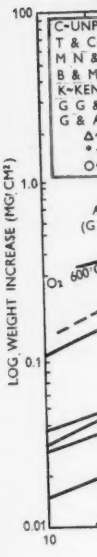
Fatigue Limit (lb/in.²)		Fatigue Ratio	Strength Reduction Factor K_f*		
nnotched	Notched Flexure		10^5 Cycles	10^6 Cycles	Fatigue Limit
21,000	8,000	0.63		1.4	2.6
10,500	6,500	0.82	1.1	1.3	1.6
56,000	12,000	0.60	2.1	2.8	4.2
15,000	6,000	0.67		1.9	2.5
18,000	8,000	0.85		1.4	2.3
20,000	8,000	0.92	1.1	1.6	2.5
24,000	8,000	0.76	1.3	1.7	3.0
xial load 21,500	19,000	0.78	1.1	1.1	1.1

atigue strength/notched fatigue strength.

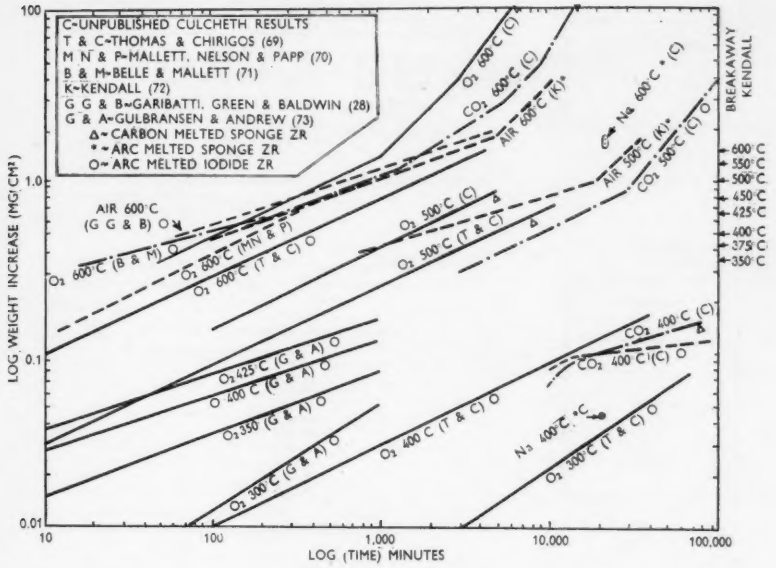
33

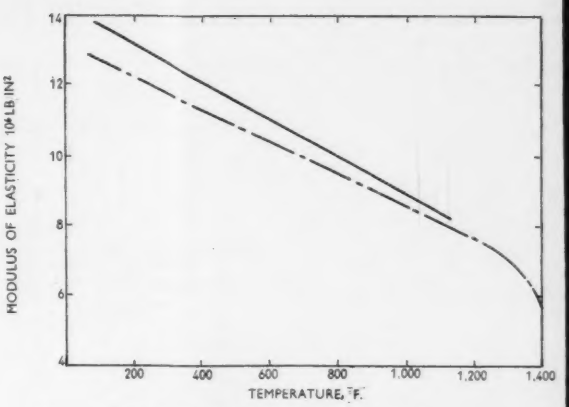
f Zirconium and Zirconium Alloys (2)

ent (°C)	Hardness	
	(R_A)	(DPH)
and slow cooled ..	33	102
and water-quenched ..	40	156
er-quenched	56	236
vater-quenched ..		111
.. ..		93
cooled	68	
cooled	58	
r-quenched	77	



Zr crucil
Zr crucil crucib Zr cruci
Zr cruci contai
Zr shee


C~UNPUBLISHED CULCHETH RESULTS
T & C~THOMAS & CHIRIGOS (69)
M N & P~MALLETT, NELSON & PAPP (70)
B & M~BELLE & MALLETT (71)
K~KENDALL (72)
G G & B~GARIBATTI, GREEN & BALDWIN (28)
G & A~GULBRANSEN & ANDREW (73)
Δ~CARBON MELTED SPONGE ZR
*~ARC MELTED SPONGE ZR
O~ARC MELTED IODIDE ZR
BREAKAWAY KENDALL
LOG WEIGHT INCREASE (MG/CM²)
LOG (TIME) MINUTES
AIR 600°C (G G & B) O
O₂ 600°C (B & M) O
O₂ 600°C (MN & P)
O₂ 600°C (T & C) O
O₂ 600°C (C)
CO₂ 600°C (C)
AIR 600°C (K)*
Na 600°C * (C)
O₂ 500°C (C)
O₂ 500°C (T & C) Δ
AIR 500°C (K)*
CO₂ 500°C (C) O
O₂ 425°C (G & A) O
O 400°C (G & A) O
O₂ 350 (G & A) O
O₂ 300°C (G & A) O
O₂ 400°C (T & C) O
CO₂ 400°C (C)
CO₂ 400°C (C) O
N₂ 400°C *C
O₂ 300°C (T & C) O
600°C
550°C
500°C
450°C
425°C
400°C
375°C
350°C



(Above) Fig. 14.—Modulus of elasticity with temperature for annealed crystal bar (full line) and Bureau of Mines sponge (dotted) zirconium (58).

(Left) Fig. 13.—Data on oxidation of zirconium in air, oxygen and carbon dioxide.

C. COMPATIBILITY

With Uranium (63)

Zirconium is compatible with Uranium up to 600°C.

TABLE C1

Compatibility of Zirconium and Uranium (63)

Type of test	Temperature of Test (°C)	Duration of Test	Penetration	Remarks
Zr crucible (0.06 in. thick) containing U pellet	1,300	9 h	Complete	
Zr crucible (0.05 in. thick) containing U pellet	1,300	15 min	Complete	
crucible in steel container Zr crucible with U pieces	1,250	2 h	0.048 in.	
Zr crucible (0.05 in. thick) containing U pellet	1,250	2 h	0.048 in.	
	1,200	4 h	0.025 in.	
	1,200	8 h	0.030 in.	
Zr sheet (0.010 in.) in contact with U pellet	900	6 weeks	0.005 in.	Slight alloy formation

TABLE C2

Temperature of Failure of Cans Fabricated from Various Materials (63)

Metal	Temperature at which 0.020 in. can is penetrated within 1 min by Uranium (°C)
Tungsten	1,500
Tantalum	1,460
Niobium	1,430
Zirconium	1,380
Titanium	1,350
Molybdenum	1,280
Tantalum coated nickel	1,130
Vanadium	1,130
Chromium	~1,000
Nickel	850–950
Stainless Steel	850–950
Nimonic	850–950
Inconel	850–950

With Gases

Hydrogen (2)

The alpha-beta transformation temperature is reduced by approximately 10°C by the addition of hydrogen.

The maximum terminal solid solubility of hydrogen in zirconium is approximately 50 at. %, and is fairly insensitive to temperature.

The maximum solubility is greater than this and corresponds to a composition in the range $ZrH_{1.75}$ to $ZrH_{1.988}$.

There are a number of discrete phases in the zirconium-hydrogen system, but there is some disagreement on their identity and ranges of homogeneity.

Absorption of hydrogen by zirconium is rapid at 300-400°C and probably occurs at lower temperatures provided the specimens have been preheated in vacuo to an elevated temperature to dissolve the surface oxide film. The effect of surface condition on rate of hydrogen uptake is shown in Fig. 16.

Carbon dioxide

Data on the corrosion rates of various grades of zirconium and Zircaloy 2 in dry CO_2 at 500°C and 120 psia are given in Table 14, and comparative oxidation rates in air, oxygen and carbon dioxide are summarized graphically in Fig. 13. The oxidation rates of selected zirconium alloys in carbon dioxide are summarized in Table C3.

TABLE C3

Tests in Dry CO_2 at 400° and 500°C, 150 p.s.i.a. Pressure on Selected Zirconium Alloys (65)

Materials	State	Corrosion rate in last 4,000 hours of test mg/cm², h	Duration of tests (h)	Wt. gains (mg/cm²)				Temperature
				1,000 h	5,000 h	8,000 h	12,000 h	
Zr 0.5% Be	Annealed sheet	1.3×10^{-4}	11,580	0.34	0.90	1.35	2.02 (11,500 h)	400°C
Zr 0.5% Cr	Annealed sheet	1.6×10^{-4}	6,300	0.54	1.34	—	—	
Zr 0.5% Cu	Annealed sheet	1.18×10^{-4}	13,050	0.19	0.78	0.94	1.16	
Zr 0.5% Fe	Annealed sheet	N.D.	6,300	0.57	1.80	—	—	
Zr 0.5% Mo	Annealed sheet	2.0×10^{-4}	6,300	0.55	1.50	—	—	
Zr 0.5% Ni	Annealed sheet	2.06×10^{-4}	13,050	0.26	1.45	2.12	2.72	
Zr 0.5% Sn	Annealed sheet	2.3×10^{-4}	13,050	0.31	1.47	2.02	2.81	
Zr 0.5% Si	Annealed sheet	1.0×10^{3}	4,760	1.0	4.8 (4,760 h)	—	—	
Zr Sponge	Annealed sheet	11.5×10^{-4}	5,000	1.64	6.22	—	—	450°C
Zr 0.5% Cu	Annealed sheet	4.5×10^{-4}	5,000	1.83	3.42	—	—	
Zr 0.7% Cu	Annealed sheet	2.4×10^{-4}	5,000	1.57	2.85	—	—	
Zr 1.0% Cu	Annealed sheet	7.8×10^{-4}	5,000	1.44	4.02	—	—	
Zr 0.5% Be	Annealed sheet	9.7×10^{-4}	5,000	2.17	5.68	—	—	
Zr 0.5% Cu .. .. 0.25% Cr	Annealed sheet	4.7×10^{-4}	5,000	1.51	3.53	—	—	
Zr 0.5% Cu .. .. 1.0% Ta	Annealed sheet	26.1×10^{-4}	5,000	7.07	17.45	—	—	

All alloy figures are given in wt. %.

Alloys in 400°C tests were manufactured from iodide crystal bar zirconium.

Empirical Rate Constants for the Corrosion of Zirconium in High Temperature Water (25)

Temperature (°F)	Temperature (°C)	Pressure (p.s.i.)	K (mg/cm²)	n
500*	260	2,000	1.5	0.264
550	287	1,048	2.4	0.270
600*	315	2,000	2.6	0.315
600	315	1,553	3.5	0.301
680	360	2,705	5.9	0.330

K and n refer to the oxidation rate law $\Delta m = Kt^n$.
* Pressurized.

TABLE C5

Effect of Temperature on Corrosion of Arc Melted Crystal Bar Zirconium (25)

Steam at One Atmosphere

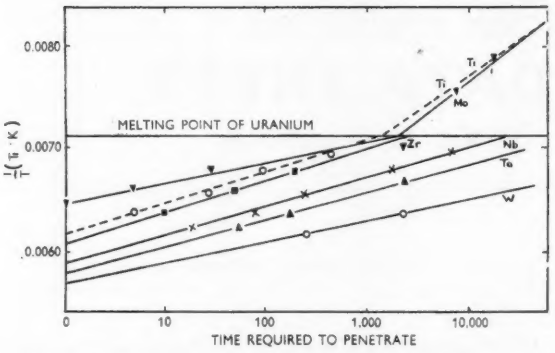
Temperature (°F)	Temperature (°C)	Exposure Time (h)	Weight Gain (mg/dm²)	Specimen Appearance
1,500	816	48	870	Grey-black. White on edges
1,150	621	42	205	Grey-black. White on edges
950	510	70	67	Grey. White areas
850	454	72	411	Grey. White spots
750	399	84	2	Black

TABLE C6

Rate Constants and Slopes for Zircaloy 2 at Various Temperatures (25)

Temperature °F	Medium	Pressure p.s.i.	Equation*
550	Water	750	$\log \Delta m = 0.24 \log t + 0.64$
600	Water	1,553	$\log \Delta m = 0.27 \log t + 0.74$
680	Water	2,705	$\log \Delta m = 0.38 \log t + 0.73$ up to $t = 110$ days
680	Water	2,705	$(\Delta m - 33) = 0.4\,(t - 110)$ after $t = 110$ days
750	Steam	1,500	$\log \Delta m = 0.40 \log t + 1.02$ up to 25 days
750	Steam	1,500	$(\Delta m - 39) = 1.0\,(t - 25)$ after $t = 25$ days

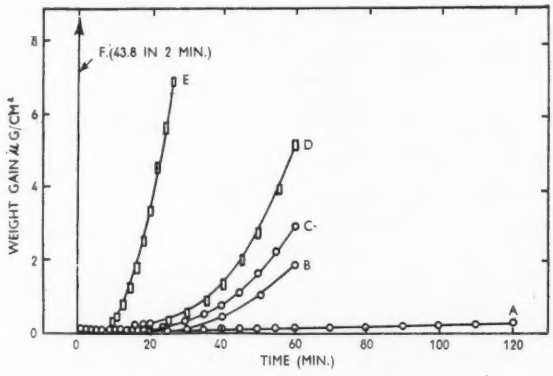
* Δm in mg/dm², t in days.
Typical behaviour of various grades of zirconium in pressurized water at 325°C is shown in Fig. 10.



(Above) Fig. 15.—Compatibility of uranium with refractory metals.

(Below) Fig. 16.—Effect of oxide on hydriding of zirconium at 150°C and 2.4 cm hydrogen (64).

A—Room temperature equilibrium film. B—Annealed with 20-hour exposure to oxygen at room temperature. C—Annealed with a 63 Å film at 150°C. D—Annealed with a 500 Å film at 250°C. E—Annealed with a 500 Å film at 275°C. F—Annealed, no film.



Sodium

Zirconium appears to be resistant to attack by oxygen-free sodium at 500°C under static and dynamic conditions.
The corrosion pattern in oxygen-bearing sodium is rather similar to that in other oxidizing media, although supply of oxygen through the film will become the rate controlling factor at levels of oxygen below 20 ppm.

TABLE C7

Corrosion of Zirconium in Flowing Sodium
(Flow rate 5.5 ft/sec)

Specimen Temperature (°C)	Filter Temperature (°C)	Oxygen Level in Na (ppm)	Exposure Time (weeks)	Mean Corrosion wt. gain (mg/in.²)	Mean Penetration of Zr (0.001 in.)	Mean Corrosion Rate (mg/cm², month)	Mean Penetration Rate (0.001 in./month)
600	340	260	2	1.65	0.28	3.30	0.57
600	130	23	2	1.70	0.29	3.40	0.59
400	120	21	2	0.045	0.008	0.09	0.016

Bismuth

Zirconium completely dissolved in bismuth at 816°C during a 50-h test period (66). The corrosion of zirconium in various binary and ternary bismuth eutectic compositions has also been studied. These were Bi-Pb, Bi-In-Sn, Bi-Pb-In and Bi-Pb-Sn eutectics, all of which gave severe attack on zirconium during 500-h tests at 650°C (67).

D. NUCLEAR PROPERTIES

TABLE D1

Comparison of Nuclear Absorption Cross-sections and Thermal Conductivities of Canning Materials

Metal	Neutron Absorption Cross-section (barns/atom)	Macroscopic Neutron Absorption Cross-section (cm^{-1})	Thermal Conductivity (c.g.s. units)
Beryllium ..	0.01	0.00123	0.32 (200°C)
Magnesium ..	0.059	0.00254	0.38
Magnox C ..	0.060	0.00261	
AM503S ..	0.164	0.00716	
Aluminium ..	0.215	0.013	0.53
Zirconium ..	0.18±0.02	0.00765	0.04

Thermal scattering cross-section .. .. 8±1 barns/atom
(average over Maxwellian distribution)
Neutron absorption cross-section of Hafnium .. .. .. 115 barns/atom

TABLE D2

Abundance and Absorption Cross-section of Isotopes of Zirconium (2)

Isotope	Isotopic Abundance (%)	Absorption Cross-section (barns/atom)
Zr^{90}	51.5	0.1 ±0.07
Zr^{91}	11.2	1.5 ±0.12
Zr^{92}	17.1	0.25±0.08
Zr^{94}	17.4	0.08±0.04
Zr^{96}	2.80	0.1 ±0.1

TABLE 4

Directional Tensile Properties of Arc Melted Low Hafnium Iodide Zirconium (37)

Material Hot-rolled at 1,400°F, Cold-rolled 66% and Annealed 1 h at 1,110°F

Direction to rolling	Test temperature (°F)	Grain size (ASTM)	Yield strength (0.2% offset) (lb/in²)	Tensile strength (lb/in²)	Elongation in 2 in. (%)	Reduction in area (%)
Parallel	R.T.	8	9,400	34,800	47	46
Parallel	300	8	8,400	23,100	53	63
Parallel	500	8	5,700	18,400	57	65
Parallel	600	8	6,000	17,900	52	57
Transverse	R.T.	8	16,900	29,000	54	67
Transverse	300	8	12,800	21,000	60	79
Transverse	500	8	8,100	14,800	59	84
Transverse	600	8	7,200	14,000	60	90

treatments to produce apparently identical microstructures, may give materials with widely differing yield strengths, tensile strengths and creep rates.[14] Tensile data determined at Culcheth at a variety of temperatures on arc-melted zirconium containing 2% Hf and on low-Hf material are summarized in Tables 2 and 3.

Rolled-sheet zirconium shows marked anisotropy in mechanical properties. Crystal bar zirconium in the as-rolled condition shows a lower yield strength and reduction in area in the transverse than in the longitudinal direction, while the converse is true of the work-hardening exponent. In the annealed condition the yield strength is lower, the work-hardening exponent smaller, and the reduction in area greater in the transverse than in the longitudinal direction. Similar results obtained for arc-melted iodide material are shown in Table 4. The effect of cold work upon the tensile properties of sponge-base zirconium is shown[15] in Fig. 5. The appreciably higher room temperature strength of sponge zirconium, compared with iodide material, is due to its higher oxygen content. However, the tensile properties of sponge-base zirconium fall off more rapidly with increasing temperature, so that at about 500°C the two materials are of comparable strength. Despite its high melting point the strength of zirconium at 500°C is small and, in order to report tensile properties satisfactorily it is necessary to specify strain rate and temperature. This applies for cold-worked metal above 200°C.

One of the most attractive characteristics of zirconium is its ductility, which is retained down to very low temperatures. This metal exhibits greater ductility than other hexagonal metals such as magnesium and zinc, which are probably capable of slip only on the basal plane. The deformation modes for zirconium have not been extensively investigated, but Rosi[16] has observed slip on $(10\bar{1}0)$ planes, and twinning on $(10\bar{1}2)$ and $(11\bar{2}1)$ planes, and it is believed that there are other deformation modes by analogy with titanium which also shows high ductility and has been studied more exhaustively.[17]

With regard to the effect of alloying on the mechanical properties of zirconium, no real systematic studies have been made taking into account the effect of melting procedure, annealing times, and grain size; but a few observations on various alloys may be of interest. Thus, of the gases which go into interstitial solid solution, nitrogen and oxygen have a marked strengthening effect. Data on the effect of oxygen, and nitrogen on the room temperature tensile properties of arc-melted zirconium are summarized in Tables 5 and 6. Hydrogen has little effect on the tensile properties above room temperature. Aluminium, with some alpha solid solubility, raises the tensile strength, but has a disastrous effect on oxidation resistance. Tin, on the other hand, with some alpha solubility, has a pronounced strengthening effect, and tin alloys (Zircaloy 2 and 3) have been used extensively in pressurized water environments. The mechanical properties of Zircaloy 2 are summarized in Table 7. Tin is an undesirable addition for use in oxidizing gases above 400°C. Dilute copper alloys are more promising from the standpoint of oxidation resistance in oxidizing gases, and copper gives an appreciable strengthening effect. Iron and chromium, beneficial additions to Zircaloy 2 for corrosion in water, have little effect on the mechanical properties of zirconium at room temperature.

Interest has also been shown in dilute alloys of high-melting elements of Group VA and VIA. Tungsten, molybdenum, niobium and tantalum all show very restricted alpha solubility in zirconium and with the exception of tantalum give appreciable strengthening for additions of the order of one or two atomic per cent. Tungsten is the most effective in this respect, but it is difficult to produce homogeneous alloys by arc melting. Once this has been achieved, the alloy can be hot worked, and shows good oxidation resistance in gases. Both tungsten and molybdenum alloys retain moderate strength at elevated temperatures, and extreme hardness can be obtained in dilute molybdenum alloys by quenching from the beta phase.

The variation of tensile strength of a number of alloys with temperature is shown in Figs. 6 and 7. It will be noted that the fall in strength with temperature of the oxygen alloys is much steeper than that for pure zirconium and the substitutional alloys. Data on the tensile properties

TABLE 5

Effect of Oxygen on the Tensile Properties of Zirconium

Specimen No.	Wt.% Oxygen	Hardness VPN (10 kg load)		Limit of proportionality (ton/in²)	Ultimate tensile strength (ton/in²)	Elongation in 1.5 in. (%)
Z.1	Nil	85	90*	10.9	14.2	25.0
Z.04	0.02	102	122	9.8	13.3	17.4
Z.03	0.04	140	129	10.4	16.6	17.0
Z.02	0.06	137	151	10.8	18.3	17.4
Z.09	0.10	178	160	13.2	20.4	8.1
Z.08	0.15	187	154	15.9	22.1	8.1
Z.07	0.16	213	163	17.9	23.4	8.1
Z.01	0.20	227	184	20.0	23.4	2.8
Z.06	0.55	251	207	21.5	23.2	1.7

* The hardness values quoted are the mean values for each end of the specimen. The material was iodide electron bombardment melted zirconium, subsequently rolled to strip 0.020 in. thick, and annealed at 750°C for 2 h. The tests were made at room temperature.

TABLE 6
Effect of Nitrogen on the Tensile Properties of Zirconium

Specimen No.	Wt.% Nitrogen	Mean hardness (VPN)	Limit of proportionality (ton/in²)	Ultimate tensile strength (ton/in²)	Elongation (%)	
					1.5 in. GL	$10\sqrt{A}$ GL
N.0	0.008	176	—	13.0	17.6	23.5
N.3	0.030	221	10.4	20.5	14.7	18.3*
N.4	0.044	225	14.5	24.5	10.8	19.9
N.2	0.069	246	18.5	28.1	15.0	20.7
N.1	0.120	260	28.3	36.4	12.0	18.6

* Specimen failed in head, and was repulled.
The material was iodide electron bombardment melted zirconium, subsequently rolled to strip 0.020 in. thick, and annealed at 750°C for 2 h.
The tests were made at room temperature.

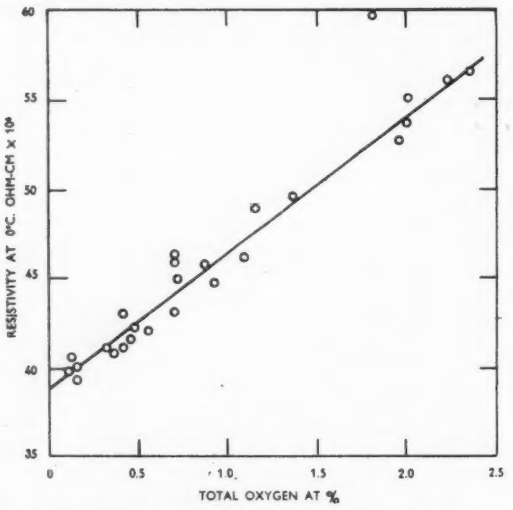


Fig. 4.—Effect of oxygen on electrical resistance of iodide zirconium (12).

of oxygen alloys at various temperatures, as determined at Culcheth, are given in Table 8. Similar effects are believed to occur with zirconium-nitrogen alloys, but the cause of this behaviour is unkown.

Extensive studies on the impact properties of zirconium have been made by Mudge[18] using the Charpy notched bar impact test. It has been shown that metals which are brittle at low temperatures will generally absorb greater amounts of energy with increasing temperature, until at some critical temperature a tough mode of failure becomes apparent. Most zirconium, whether sponge base or iodide material, contains sufficient hydrogen to render it susceptible to embrittlement. To develop embrittlement it is necessary to heat to above 315°C and then cool at a rate slower than the critical rate to a temperature below 260°C. This critical cooling rate depends on the hydrogen content of the material. Thus, water quenching of material containing 50 p.p.m. from 315°C is sufficient to suppress precipitation of zirconium hydride. With hydrogen contents of the order 100 to 500 p.p.m. water quenching is insufficient and a faster cooling rate would be necessary to avoid embrittlement. Mudge concluded that as little as 10 p.p.m. of hydrogen in zirconium is sufficient to cause noticeable embrittlement in the quenched and aged condition.

The Charpy impact strength of hot-rolled, annealed plate varies markedly with the orientations of the specimens, and the notch with respect to the rolling plane and direction. Annealed zirconium can retain high-impact strength down to liquid nitrogen temperatures, in contrast to other hexagonal metals such as magnesium or zinc.

TABLE 7
Tensile Properties of Commercial Arc Melted Hafnium Containing Zircaloy 2

Specimen No.	Test temperature (°C)	Limit of proportionality (ton/in²)	Ultimate tensile strength (ton/in²)	Elongation (%)	Reduction of area (%)
PQB. 1a	R.T.	35.3	47.8	24	47
PQ. 31	200	25.8	34.8	28	54
PQ. 30	400	19.5	23.2	24	60
PQ. 32	500	14.3	17.7	33	79
PQ. 33	600	7.14	9.6	50	97
PQ. 34	700	3.56	4.28	66	>99
PQ. 35	800	1.52	2.23	91	>99
PQB. 2a	900	0.56	0.68	93	>99

Specimens were from a billet with the following composition:
Oxygen 0.11%: Nitrogen 0.02%: Hydrogen 0.0008%: Tin 1.55%: Chromium 0.09%: Nickel 0.05%.
Specimens were hot-rolled with average hardness 212 VPN and estimated grain size 0.015 mm.

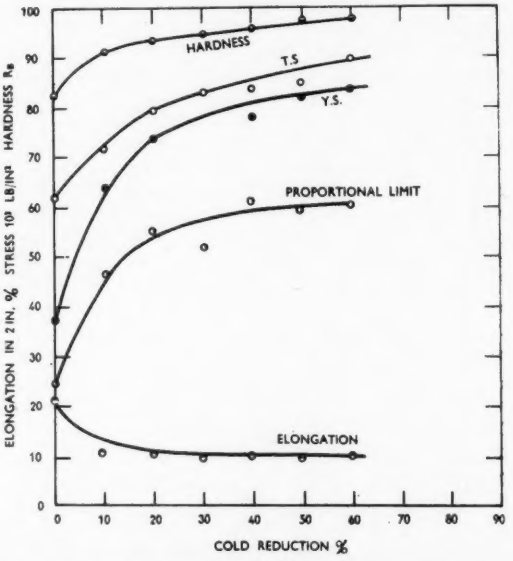
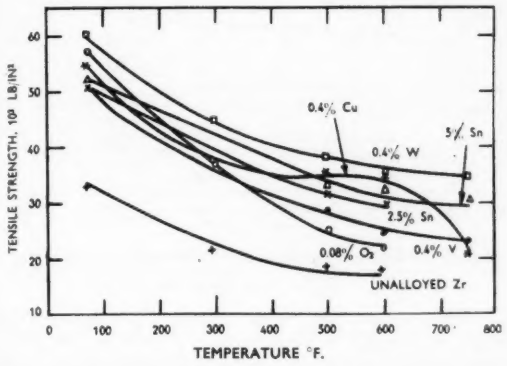


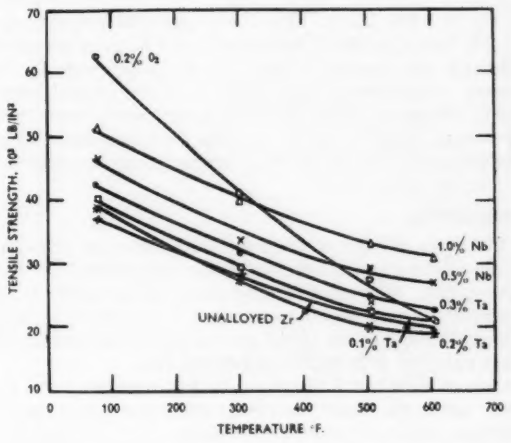
Fig. 5.—Effect of cold work on tensile properties of induction-melted sponge zirconium (15).

Creep

Results available on the creep properties of zirconium are relatively scarce and wide differences between sponge-base and iodide-base materials are observed. Lustman and Kerze[2] have summarized data on the creep properties of zirconium sheet at 260°C (Table 9). The results of Schwope and Muehlenkamp[19] showed that, for the arc-melted iodide sheet which they used, the creep rate did not depend on the relation of the axis of tension to the rolling direction, Manjoine and Pollock[20] found that for other material, the creep strength for the transverse rolling

Effect of temperature on tensile strength of alloyed and unalloyed zirconium (37). Fig. 6 (below) low-hafnium. Fig. 7 (right) high-hafnium.





directions of annealed zirconium was higher than that for the longitudinal, below a critical creep rate, but that the effect was reversed above this rate. The discrepancies may be due to differing gas contents in the metal. Results of creep and stress rupture tests carried out at the Culcheth laboratories of the U.K.A.E.A. on arc-melted sponge containing 2% Hf in the temperature range 300-550°C are summarized in Tables 10 and 11. Creep tests were conducted in an inert atmosphere on extruded material, and on samples annealed at 700°C for 20 hours after extrusion.

From the limited results available it appears that the fabrication and annealing history is just as important in affecting the creep properties of zirconium as in the case of tensile properties.

In view of the poor high-temperature mechanical properties of zirconium improvements in creep properties must be sought in alloys. A number of alloys, including compositions from the zirconium-molybdenum, zirconium-tin, zirconium-aluminium, zirconium-niobium and the zirconium-molybdenum-titanium systems have been prepared and examined by the Admiralty Materials Laboratory[21, 22, 23] with this end in view. In the light of the temperatures and strain rates chosen (i.e., 300°C/20,000 p.s.i. in air: 450°C/6,000 p.s.i.: 600°C/3,000 p.s.i. in argon) alloy systems were selected capable of modification by precipitation from supersaturated solid solutions or eutectoid reactions, as a basis for the improvement of creep properties.

Promising results on binary tin alloys creep tested in air, at 20,000 p.s.i. and 300°C, are shown in Fig. 8. It will be observed that progressively higher tin contents decrease primary and secondary creep deformation. Thus the 2.27% tin alloy gave 0.12% total creep deformation in 4,000 hours, whilst the 6.7% tin alloy gave only 0.005% in the same period. These two alloys were then tested at 30,000 p.s.i. at 300°C in air. While the higher alloy showed only a total creep deformation of 0.017% in 4,000 hours, the creep strain of the 2.27% tin alloy was much higher, being 0.56% in 2,000 hours, mostly as primary creep. A 6.7% tin alloy and a 9.7% niobium alloy showed the best creep resistance of the alloys tested at 450°C and 6,000 p.s.i. A two-fold improvement in creep resistance of a 0.8% Sn alloy was effected by a heat treatment at 975°C to increase the alpha grain size. It was also found that the minor additions of iron, chromium and nickel to the binary tin alloys, to produce a Zircaloy composition, had beneficial effects on the creep rate at 450°C/6,000 p.s.i. The 9.7% niobium alloy exhibited decomposition of the beta phase on ageing, and a heat treatment at 550°C for 20 hours was found to be beneficial in giving a total creep deformation in 5,000 hours at 20,000 p.s.i. and 300°C of 0.04%, whilst a specimen in the extruded condition gave this same deformation in 750 hours at 16,000 p.s.i.

The creep strength of the tin-based alloys falls off rapidly at 600°C as may be seen from Fig. 9. At this temperature, the 7.6% molybdenum and the 1.5% aluminium are

TABLE 8

Variation of Tensile Properties of Zirconium-Oxygen Alloys with Temperature

Specimen No.	Condition	Chemically determined Oxygen level (ppm)	Hardness (VPN* 10 kg load)	Tensile properties			
				Test temp. (°C)	L. of p. (ton/in²)	Ultimate tensile strength (ton/in²)	Elongation 1 in. length (%)
ZR.1 ..	As received.	920	191	R.T.	13.8	23.5	29
ZR.2 ..		N.D.	196	200	6.1	12.7	50
ZR.4A ..		1,000	197	300	—	7.0	36
ZR.4B ..		N.D.	192	400	3.3	7.0	38
ZR.4C ..		N.D.	186	500	2.5	5.5	38
ZR.3 ..	Nominal 1,000 ppm Oxygen added.	1,960	262	R.T.	20.3	31.8	21
ZR.5 ..		N.D.	265	200	10.3	15.4	34
ZR.6 ..		2,300	258	300	4.2	9.1	43
ZR.7 ..		N.D.	260	400	3.5	7.2	36
ZR.8 ..		N.D.	265	500	3.3	5.6	54
ZR.9 ..	Nominal 2,000 ppm Oxygen added.	3,360	317	R.T.	15.4	34.8	16
ZR.10 ..		N.D.	314	200	11.4	19.5	35
ZR.11 ..		4,300	312	300	6.1	12.4	33
ZR.12 ..		N.D.	318	400	4.5	8.8	36
ZR.13 ..		N.D.	332	500	3.6	6.6	42

The starting material was commercial arc-melted hafnium containing zirconium.
* Mean of eight impressions.
N.D. = Not determined.

markedly superior. Both these alloys have a creep rate of 1% in 1,000 hours. The 7.6% molybdenum was aged for 200 hours at 600°C before test, and is quite promising although the primary creep rate is rather high. The ternary composition examined, a 7.8% molybdenum, 10.3% titanium alloy, showed surprisingly poor creep resistance, being inferior to the corresponding binary molybdenum alloy at the three temperatures examined.

Compatibility

The basic pattern of the long-term corrosion behaviour of zirconium in oxidizing media was first established from experiments with high-temperature pressurized water. Thomas[24] showed that the corrosion of zirconium in water is characterized by an initial period where the scaling rate has a cubic or even higher exponent, i.e.,

n has a value of 3 or more in the relation $\Delta w^n = kt$, where Δw is the weight increment after time t, k is the rate constant, and n a numerical constant.

At this stage the oxide film has a lustrous black appearance and shows excellent coherence with the metal. After oxidation has proceeded for some time at a given temperature, a change in rate law takes place at some critical oxide thickness giving a more rapid corrosion rate, with n in the above relation approximately 1. This rate change is generally accompanied with the appearance of non-adherent white corrosion product on the surface of the metal, and a loss in the protective properties of the film.

TABLE 9

Creep Properties of Zirconium Sheet at 260°C (19)(20)

Material	Temp. (°C)	Stress (lb/in²)	Test time (h)	Minimum creep rate (%/hour)	Total extension %
Arc melted iodide*	260	11,000	1,800	0.000058	2.42
Arc melted iodide*	260	13,000	574	0.00064	7.93
Arc melted iodide*	260	14,000	262	0.0015	7.9
Arc melted iodide*	260	17,000	343	0.047	54.4
Arc melted iodide†	260	10,000	2,000	0.00003	0.31
Arc melted iodide†	260	12,000	2,000	0.00004	0.64
Arc melted iodide†	260	14,000	2,000	0.00008	2.35
Arc melted iodide†	260	16,000	2,000	0.0003	5.2
Arc melted iodide‡	260	16,000	2,000	0.0028	14.4
Induction melted sponge§ ..	260	12,000	1,710	0.000035	0.67
Induction melted sponge§ ..	260	10,000	1,230	Nil	0.38

* Forged and rolled at 760°C, cold rolled 50%, annealed ½ h at 600°C; grain size 0.025 mm; yield strength at 260°C, 5,400 lb/in².
† Forged and rolled at 627°C, cold rolled 47%, annealed 1 h at 593°C; grain size 0.020 to 0.030 mm; yield strength at room temperature, 19,900 lb/in², at 260°C, 10,700 lb/in².
‡ Same as preceding specimen except yield strength at room temperature is 15,800 lb/in².
§ Forged and rolled at 1,000°C, cold rolled 30%, annealed 1 h at 704°C; yield strength at 260°C, 11,500 lb/in².

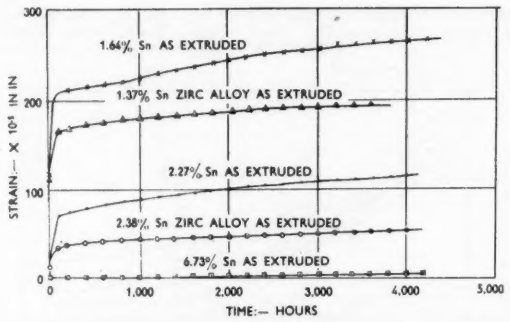


Fig. 8.—Creep tests at 300°C and 20,000 p.s.i., in air (23).

This phenomenon has been termed "breakaway" by American workers.

Thomas[25] has examined the kinetics of the corrosion of unalloyed zirconium in water and steam, in relation to such variables as temperature, impurity content, metallurgical structure and surface condition. He has shown that the corrosion resistance of the metal is markedly dependent on the impurity content of the metal.

Nitrogen is one of the most injurious impurities, and precautions must be taken during zirconium fabrication to keep atmospheric contamination to a minimum. Fig. 10 shows characteristic zirconium corrosion curves in water at 325°C (obtained at Culcheth). It will be observed that specimen Z6 corroded rapidly almost from onset, and this was associated with a high nitrogen content in the metal. A systematic study carried out by Lustman[26] showed that samples containing more than 40 p.p.m. nitrogen exhibit "breakaway" within a short time in water at 315°C, the transition time decreasing with increasing nitrogen content. Contents above 150 p.p.m. resulted in the rapid disintegration of specimens. (See Fig. 11.)

Other deleterious impurities in zirconium are considered to be carbon, hydrogen, aluminium, titanium and silicon. The corrosion rate of zirconium in water is extremely sensitive to surface condition. Machining and abrading the surface of zirconium give rise to a layer of disturbed metal at the surface, and extending for some depth beneath it. This disturbed layer corrodes extremely rapidly and produces loose white scale from the onset. In order to obtain a representative corrosion rate it is necessary to remove the disturbed material by etching with a HF/HNO_3 solution, which must be thoroughly rinsed off before it dries on the specimen. Waldman and Cohen[27] have shown in heat transfer studies that if heat is applied through the

TABLE 10

Creep Rupture Data on Commercial Arc Melted Zirconium Containing 2% Hf at 300°, 350° and 400°C

Specimen No.	Temperature (°C)	Stress (ton/in²)	Times to reach specified % creep strain (h)					Min. creep rate (h^{-1})	Final strain (%)	Duration (h)	Remarks
			0.50	1.0	2.0	5.0	10.0				
MC 38	300	10.0				3	6	3.7×10^{-3}	37	28	Fractured
LY 38	300	9.5						2.9×10^{-3}	35	35	Fractured
MC 32	300	9.16							42	23.5	Fractured
LY 36	300	9.0			1			2.5×10^{-7}	2.705	5,000	Continuing
LY 33	300	8.5	2					1.0×10^{-6}	0.72	1,440	Test discontinued
LY 35	350	9.5							43	1.5	Fractured
LY 37	350	9.0							32	19	Fractured
MC 33	350	8.7				55	210	3.2×10^{-4}	39	431	Fractured
LY 32	350	8.5		11	455	1,267		19.0×10^{-4}	32	2,098	Fractured
LY 30	350	7.4	354	958				10.5×10^{-4}	35	4,769	Fractured
LY 34	400	8.5							31	22	Fractured
LY 39	400	7.5		7	22	72	97	6.3×10^{-4}	42	178	Fractured
MC 34	400	6.5		5	12	55	115		52	250	Fractured

MC numbers were from billet with the following analysis. Oxygen 0.11%: Nitrogen 0.009%: Hydrogen 0.003%: Carbon 0.03%.
LY numbers were from billet with the following analysis. Oxygen 0.23%: Nitrogen 0.016%: Hydrogen 0.003%: Carbon 0.05%.
All specimens were annealed at 700°C for 20 h. This resulted in a decrease in hardness from 172 to 160 VPN, and an average grain size of 0.03 mm.
Tests were carried out on miniature Denison machine, with specimens of gauge length 1 in. and cross sectional area 0.025 in².

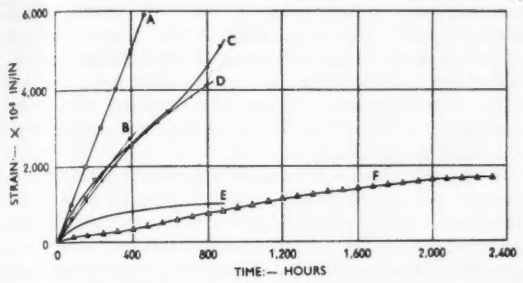


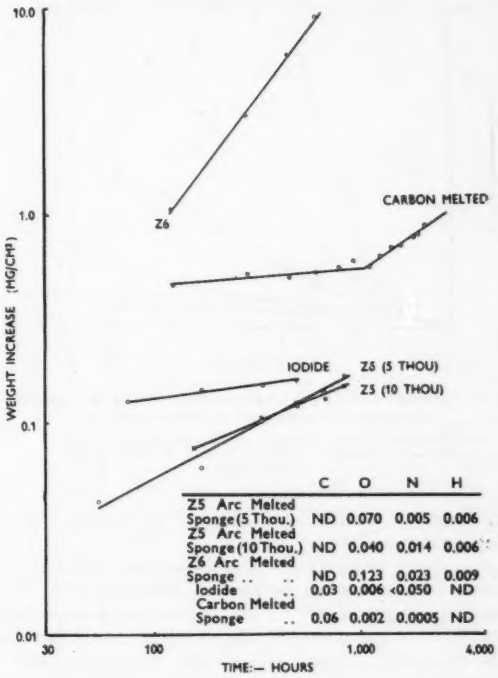
Fig. 9.—Creep tests on zirconium alloys at 600°C and 3,000 p.s.i. (23).

A, 1.37% Sn Zircaloy as extruded; B, 2.38% Sn Zircaloy as extruded; C, 10.3% Ti 7.8% Mo aged 200 h at 600° C; D, 2.27% Sn as extruded; E, 7.6% Mo aged 200 h at 600° C; F, 1.48% Al as extruded.

metal and oxide layer at a high power level, excessive temperatures may be attained at the oxide-metal interface where thick oxide films exist, and an accelerated rate of corrosion will be established.

The corrosion behaviour of sponge-base zirconium and, to a lesser extent, iodide material, varies widely from batch to batch in high-temperature water, and American workers[24] embarked on an extensive alloy programme in an effort to produce a material with a more reproducible corrosion behaviour in which they could utilize sponge-base material. They also attempted to eliminate or delay "breakaway" and to reduce the "post-breakaway" corrosion rate. A considerable amount of work has been done on zirconium-tin alloys. Although the corrosion rate is higher than that for crystal-bar iodide zirconium, and the corrosion rate increases with increasing tin content, a fundamental difference is that the oxide film remains adherent for a considerable time after the change in rate law occurs. With a 2.5 wt.% Sn alloy the rate transitions occurred within 60 days at 315°C, compared with about one year with good iodide material. In addition to promoting oxide film adherence, tin tends to counteract the harmful effect of nitrogen in sponge by decreasing the corrosion rate. Fig. 12 shows that there is an optimum tin content at which the harmful effects due to a certain concentration of nitrogen are counteracted. The amounts of tin claimed to compensate for various concentrations of nitrogen are given in Table 12.

Binary additions of iron, nickel and chromium to zirconium of the order of 0.1 wt.% improve corrosion resistance. Alloys containing 0.1 to 0.5 wt.% of these elements show corrosion resistance which is fairly insensitive to composition. Additions above 0.5 wt.% show decreased corrosion resistance in high-temperature water. It was found that a 1.8 wt.% tin alloy failed in water after



	C	O	N	H
Z5 Arc Melted Sponge (5 Thou.)	ND	0.070	0.005	0.006
Z5 Arc Melted Sponge (10 Thou.)	ND	0.040	0.014	0.006
Z6 Arc Melted Sponge	ND	0.123	0.023	0.009
Iodide ..	0.03	0.006	<0.050	ND
Carbon Melted Sponge ..	0.06	0.002	0.0005	ND

Fig. 10.—Corrosion of zirconium in water at 325°C.

14 days at 360°C, but that additions of small amounts of a ternary addition of iron, chromium or nickel produced a marked improvement. The American workers finally settled upon a composition of 1.5 wt.% Sn, 0.12 wt.% Fe, 0.10 wt.% Cr and 0.05 wt.% Ni which they called Zircaloy 2, and which enabled them to use Kroll sponge in commercial production. A summary of the corrosion data on binary alloys in high-temperature water is given in Table 13.

The pattern of oxidation in gases such as oxygen, air and carbon dioxide follows the general pattern of aqueous corrosion in as far as there is an initial period of scaling characterized by a rate which is intermediate between parabolic and cubic, when a lustrous black film is formed. This is followed by a rate change to a linear or divergent scaling rate, with the formation of white non-adherent oxide patches on the surface. The critical thickness of oxide at which the rate change occurs increases with increasing temperature (i.e., at 500°C in CO_2 it has been observed to occur at a weight gain of ~0.9 mg/cm² and at 800°C at a weight gain of 4 to 5 mg/cm²) and after progressively shortening times. The critical thickness may also depend

TABLE 11

Creep Rupture Data on Commercial Arc Melted Zirconium Containing 2% Hf at 500 and 550°C

Specimen No.	Condition	Average grain size (mm)	Hardness (VPN)	Temp. (°C)	Stress (lb/in²)	Times to reach specified strains (h)					Terminal strain (%)	Time (h)	Min. creep rate ($h^{-1} \times 10^{-4}$)
						0.05	0.1	0.2	0.5	1%			
—	Annealed	—	—	500	1,000	360	1,096	—	—	—	0.117	1,340	0.7
MC 16 ..	Annealed	0.036	137	500	1,500	113	280	610	1,609	—	0.61	1,986	3.1
MC 15 ..	Annealed	0.039	139	500	2,000	11	43	154	546	—	0.822	1,001	7.8
MC 13 ..	Annealed	0.038	139	500	2,500	4	8	30	104	268	2.209	986	14.0
MC 7 ..	As extruded	0.032	131	500	1,500	220	640	1,200	2,300	—	0.72	3,259	1.5
MC 1 ..	As extruded	0.034	153	500	2,000	297	705	1,335	—	—	0.217	1,440	1.42
MC 14 ..	Annealed	0.034	141	550	500	284	555	980	—	—	0.253	1,124	—
MC 9 ..	Annealed	—	—	550	750	350*	—	—	—	—	0.041	266	1.1
MC 3 ..	Annealed	0.04	139	550	1,000	140	260	450	790	1,240	1.909	2,063	11.0
MC 10 ..	Annealed	0.041	137	550	1,500	5	11	28	95	276	1.061	306	24.0
MC 5 ..	Annealed	0.043	137	550	2,000	—	4	7	22	68	2.46	315	43.0
MC 11 ..	Annealed	—	—	550	3,000	—	—	—	2	6.6	1.93	21	520.0
MC 6 ..	As extruded	0.030	149	550	1,500	25	66	148	397	—	0.588	476	12.0

* Result by extrapolation.
The annealing treatments and test pieces were identical with those reported in Table 10.

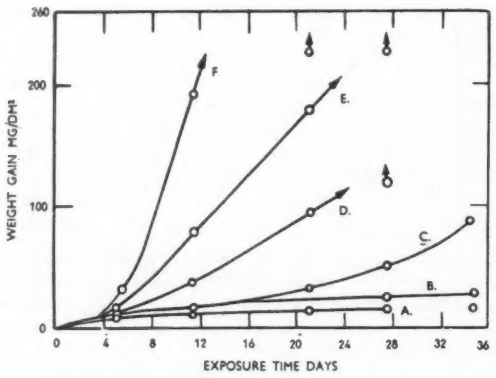


Fig. 11.—Effect of nitrogen content upon corrosion resistance of crystal bar zirconium in water at 600°F.

Nitrogen contents, nominal and analysed, in ppm are as follows: A, 30–30; B, 40–30; C, 50–30; D, 70–40; E, 80–90; F, 140–130.

upon impurity content and degree of thermal cycling during oxidation.

It has been observed, at Culcheth, that the effect of impurity content of zirconium on oxidation rate is of minor importance at 400°C, but of overriding importance at 500°C. Thus samples of carbon-melted, arc-melted, and iodide zirconium show very similar oxidation rates at 400°C, while extrapolated values for penetration after three years at 500°C indicate a rate of attack four times as great for the carbon-melted material as for the iodide material. Zircaloy 2 is not particularly good in an oxidizing gas environment. It would be acceptable for use in carbon dioxide at 400°C, but unacceptable at 500°C, owing to the high penetration rate, which is roughly four times as great as that for production arc-melted material obtained in the U.K. These results are summarized in Table 14.

It is not believed that nitrogen contents up to 250 p.p.m. in zirconium have a very deleterious effect on corrosion resistance in CO_2 at elevated temperatures, in contrast to water environments. On the other hand, titanium and aluminium are highly undesirable impurities. Beneficial additions in small quantities appear to be molybdenum, tungsten and copper. Fig. 13 summarizes zirconium corrosion rates at various temperatures up to 600°C in air, oxygen and CO_2. Taking into acccount the varying impurities of the materials used, it will be observed that the oxidation rates in the three media do not differ widely. At higher temperatures in air, however, incorporation of zirconium nitride into the film occurs with serious disruption effects in the films, and a curious growth phenomenon in the metal.[28] At these temperatures extensive solution of oxygen and nitrogen from the oxide film into the metal occurs, causing modification in mechanical properties.

The oxidation of zirconium in liquid sodium follows a similar pattern to that in gaseous media, with formation of a coherent film followed by film breakdown. As with gases, solution of the oxide into the metal occurs at temperatures of the order of 600°C and above, causing deterioration in impact properties. In view of this, it is general practice to use hot traps in the sodium circuit, to reduce zirconium oxidation. The hot traps generally utilize zirconium or a zirconium-titanium alloy sheet, maintained at 50 to 100°C above the temperature of the zirconium in the circuit.

In general the resistance of zirconium in acidic and alkaline media is excellent, and comparable with that of tantalum. The potentialities for this metal in chemical industry where severe corrosion problems arise would appear to be outstanding. Zirconium is not attacked by concentrated HCl or HNO_3, or by 50% NaOH or H_2SO_4 at 100°C. Concentrated H_2SO_4 and 75% H_3PO_4 both attack zirconium at this temperature.[29]

Purity is an important factor in tests in hydrochloric acid. Arc-melted zirconium shows low corrosion rates and no signs of embrittlement in this medium, whereas graphite-melted zirconium shows severe embrittlement with very high corrosion rates.[30, 31] Induction-melted zirconium is almost completely resistant to attack by organic acids, and by inorganic chloride solutions, with the exceptions of ferric and cupric chloride solutions. In this case there is a type of embrittlement attack, the depth of which is proportional to the concentration of the solution, and to the temperature. The corrosion resistance of high and low hafnium content iodide zirconium to acids and alkalis is summarized in Table 15.

Fabrication and Joining

Gas content of the metal is again of considerable importance in cold-working operations. Oxygen and nitrogen increase the low-temperature yield strength, and decrease ductility, so that the cold-forming properties of iodide zirconium are markedly superior to those of sponge. However, both materials can be satisfactorily hot-worked, as the effect of gases on the mechanical properties does not persist at higher temperatures.

Operations involving the handling of small ingots, can often be best carried out by cladding prior to forging and rolling to strip, thus avoiding atmospheric contamination. The strip can then be decanned and cold rolled to the required thickness. Choice of the cladding material is governed by the relative hardness of clad and matrix which should not differ greatly; the propensity to alloy formation between the two materials; and the surface

TABLE 12

Concentration of Tin Required to Compensate for Various Concentrations of Nitrogen (24)

Tin content (wt.%)	Nitrogen content (ppm)
0.5	200
1.0	300
2.0	600
2.5	700
3.0	800

TABLE 13

Summary of Aqueous Corrosion Data on Binary Alloys (24)

Alloying element	Range of composition (wt.%)	Effect
Mo	0–8	Does not appear to be beneficial: not harmful in small quantities.
Nb	0–10	Tendency to counteract nitrogen. Much less effective than tin.
	10–30	Harmful.
Sb	0–3	Tendency to counteract nitrogen. Much less effective than tin.
U	0–100	Corrosion resistance decreases with increasing uranium content.
Si	0–1	Harmful.
Ti	0.1–100	Corrosion resistance extremely poor up to at least 20 w/o.
Ta	0.05–10	Corrosion resistance decreased.
Hf	0–2	No effect.
Co	0–1.2	Corrosion resistance decreased slightly.
W	0.7	Corrosion resistance decreased.
Cu	0–1.5	Corrosion resistance decreased.
Mn	0–5	Corrosion resistance decreased.
Al, Cd, Ce, Ca	—	Harmful.
Mg, Na, Pb, Zn	—	Harmful.
La, Ga, V, Be	—	Harmful.

finish of the zirconium after removal of the sheath. For example, in extrusions, mild steel can be used successfully in the temperature range 750-815°C. Below this temperature the clad material tends to rupture, while above 815°C interaction between steel and zirconium occurs. Copper sheathing has also been used successfully up to 800°C. Sheathing is less attractive in larger scale operations, and the procedure adopted is to heat the ingots in either gas or electric furnaces at temperatures in the region of 1,000°C for one or two hours, followed by forging with a starting temperature in the range 760-840°C.[32] During these operations, gross oxidation occurs, with the formation of an underlying zone of brittle material, due to the diffusion of oxygen from the oxide film into the metal. Provided the material is reasonably large in section, this is not too serious, and the contaminated material can be removed by grit blasting and pickling, followed by surface grinding prior to hot rolling. Reduction from slab to sheet is generally done after a single heating operation to avoid excessive surface contamination. It is stated by Harford[32] that reductions of up to 35% per pass can be achieved with sponge zirconium without edge cracking.

One of the main problems in zirconium working is the tendency of the metal to gall or seize on die walls during wire drawing or extrusion operations. This may be overcome by the use of lubricants, or the presence of a thin oxide film on the metal.

A considerable amount of work has been done on developing the powder metallurgy of zirconium, as material was only available in this form (from bomb reduction processes) prior to the development of the Kroll and Van Arkel processes. Nowadays, powder is prepared via comminution of the hydride, as the metal is too ductile to be ground mechanically. Massive material is hydrided at 800°C with subsequent grinding in an inert gas to prevent oxygen and nitrogen pick-up, and to prevent ignition, as the material is extremely pyrophoric.

Zirconium powder is recovered from the hydride by vacuum decomposition at high temperatures. Cold compacted zirconium powder can be vacuum sintered or sintered in an extremely pure inert gas atmosphere at 1,300°C. The former process has the advantage that the hydride can be sintered direct after compaction. The decomposition of the hydride thus presents a more extended surface area aiding the sintering process. Properly sintered zirconium shows high ductility, and can be readily cold rolled, and the sintering process has useful industrial applications.

Zirconium has excellent welding characteristics. Hot or cold cracking does not occur in arc-welded sections up to ½-in. thick according to Paasche and Killin.[33] This is due to a small degree of distortion during welding, owing to the low coefficient of thermal expansion, and the small residual stresses resulting from the low modulus of elasticity of zirconium.

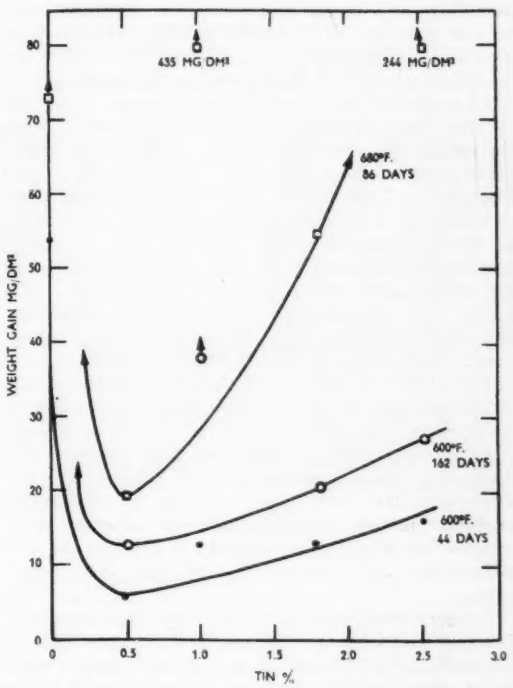


Fig. 12.—Effect of tin content on corrosion resistance of arc-melted sponge base alloys (24). (Corrosion resistance of unalloyed material is caused by 60 ppm nitrogen.)

The use of fluxes during welding is unnecessary and in general inclusions are not formed due to the high solubility of the oxide and nitride in the metal. However, gas contamination during welding is the most serious problem encountered with zirconium, and inert gas shielded arc-melting techniques have been developed. (Butt welds up to 10 ft long have been made in the U.S. for the Sodium Reactor Experiment using this technique.) Flash welding has been used to produce ductile joints between stainless steel and zirconium such as would be necessary in closed cooling systems. Attempts at brazing zirconium have been rather unsuccessful due to intermetallic compound formation, and the difficulty of removing zirconium oxide films.

Effects of Irradiation

Neutron bombardment of zirconium is known to affect its density, hardness, impact strength, tensile properties,

TABLE 14

The Corrosion of Zirconium and Zircaloy 2 in Dry Carbon Dioxide at 120 p.s.i.a.

Temperature (°C)	Material	Extrapolated weight gain (mg/cm²)		Extrapolated penetration (0.001 in.)*	
		after 1 year	after 3 years	after 1 year	after 3 years
400	Iodide Zr	0.29	0.48	0.05	0.085
400	C melted Zr	0.33	0.56	0.06	0.097
400	Arc melted Zr I.C.I. (Billet Z5)	0.50	0.96	0.087	0.17
400	Arc melted Zr I.C.I. (Billet Z6)	0.41	0.66	0.071	0.115
400	C melted Zircaloy	0.52	0.8	0.090	0.14
500	Iodide Zr	11.0	31.0	1.91	5.4
500	C melted Zr	33.0	120.0	5.75	21.0
500	Arc melted I.C.I. (Billet Z5)	27.0	140.0	4.7	24.4
500	Arc melted I.C.I. (Billet Z6)	23.0	100.0	4.0	17.4
500	C melted Zircaloy	130.0	450.0	22.6	78.0

* The penetration rates are not multiplicative as they are measured in both pre- and post-breakaway periods.

creep rate and electrical resistivity. Unfortunately, as most of the work is classified, only a limited number of results can be discussed here. Kemper and Kelly[34] studied the effects of neutron irradiation on the tensile properties and hardness of zirconium produced by the Kroll process, also the effect of various degrees of prior cold working on the extent of radiation damage. Annealed and work hardened specimens were irradiated at various neutron doses up to 2.4×10^{20} nvt (thermal) at a temperature of about 60°C. The most pronounced effects of irradiation on tensile properties were noted in yield strength, with maximum increase (65%) in the annealed material, becoming progressively less after increasing amounts of cold work. The increase in ultimate tensile strength and decrease in ductility were less sensitive to previous cold work. Saturation of the irradiation effects occurred at about 5×10^{19} nvt and it is thought that further irradiation would give rise to only small changes in hardness and tensile properties. Recovery of the irradiation damage was observed at a lower temperature than recovery of cold work; 40% recovery occurred in 100 hours at 300°C. The tensile data are summarized in Table 16. The maximum hardness increase on irradiation was observed with the annealed material (50 to 70 Rockwell G), and the increase in hardness was progressively less with increasing cold work.

A theory to account for the effects of fast neutron radiation on the above properties has been advanced by Dienes.[35] The major effect of irradiation is a displacement effect, in which atoms are knocked out of their lattice positions, forming vacancies and interstitials. The interaction of the interstitial atoms or groups, with the stress field of dislocations, in such a way as to impede the motion of dislocations, is thought to be responsible for the hardening and the increase in the stress to produce plastic flow. This blocking of the movement of dislocations by interstitials becomes less important at high strain values, where the mobility of dislocations is more affected by interaction with other dislocations. This is in line with experimental findings that the ultimate strength and total ductility are not appreciably affected by irradiation.

Interesting evidence for the transformation of bulk monoclinic zirconia to the cubic modification has recently been published by Wittels and Sherrill.[36] These authors claim to have effected the transformation by using a fast neutron source and irradiating to 2×10^{20} nvt. This effect has also been observed during the irradiation of Zircaloy 2 in uranyl sulphate solution at high temperature, when a cubic form of zirconia, which is not normally found below temperatures of the order of 1,400°C, has been observed in the oxide film. It thus appears that the transformation to cubic zirconia can occur either under fast neutron bombardment or fission fragment bombardment. The implications of this from the standpoint of oxide film coherence under irradiation have not yet been assessed.

General Remarks

The development of zirconium has been a by-product of the growth of the nuclear energy industry, principally in the United States. Although it was discovered as early as 1824, a further century elapsed before zirconium was produced in pure ductile form. This was rendered possible by the development of modern vacuum techniques, and the Van Arkel-de Boer process. At this stage the material was extremely expensive as it was produced in laboratory quantities only, and no particular use could be foreseen for it.

In 1948 interest in the metal revived, when it was discovered that high neutron capture cross-sections hitherto measured were due to hafnium impurities and that the pure material had a cross-section of the order of 0.2 barns. About this time the U.S. Bureau of Mines began to develop the Kroll process to produce sponge zirconium on a larger scale, at a reduced cost.

The pattern of development since 1948 has largely hinged on the corrosion-resistant properties of iodide zirconium in high-temperature water environments, and the requirement for a sponge-based alloy of equal corrosion resistance for use as fuel component and cladding in pressurized water reactors. Such a reactor has not yet been developed in

Le Zirconium et ses Alliages

Des valeurs choisies pour les propriétés physiques, chimiques, mécaniques et nucléaires du zirconium et de ses alliages sont présentées sous forme de feuilles de données. Une discussion des possibilités présentées par le zirconium et ses alliages pour éléments de boîtes et de noyau dans les réacteurs à gaz pressurisé et à refroidissement à eau, par rapport aux autres matériaux de canning à section transversale à capture réduite de neutrons, y figure. Les procédés principaux pour l'extraction de l'hafnium ont été donnés dans leurs grandes lignes sous forme de tableau. Les facteurs qui influent sur la résistance à la corrosion du zirconium dans l'eau pressurisée sont discutés en détail, ainsi que les travaux qui amenèrent l'adoption de l'alliage à base éponge, le Zircaloy 2, aux Etats-Unis. L'effet de la contamination par les gaz sur la fabrication, et sur les propriétés physiques et mécaniques, et la résistance à la corrosion du zirconium sont soulignés dans tout l'article. Les travaux sur le développement des alliages s'oxydant à température élevée et résistant au cheminement, sont aussi discutés brièvement, ainsi que l'effet de l'irradiation sur les propriétés mécaniques et la résistance à la corrosion.

Zirkon und seine Legierungen

Es werden in der Form von Zahlungstafeln ausgewählte Werte hinsichtlich der physikalischen, chemischen, mechanischen und atomphysikalischen Eigenschaften von Zirkon und seinen Legierungen gegeben. Die Möglichkeiten, Zirkon und seine Legierungen als Material für die Hülsen und im Kern von mit Druckgas und Druckwasser gekühlten Reaktoren zu verwenden, werden diskutiert und verglichen mit der Verwendung anderen Hülsenmaterials von geringem Neutronen-Absorptions Querschnitt. In Tabellenform werden weiter die Haupt-Verfahren für die Abtrennung von Hafnium dargestellt. Die Faktoren, die den Widerstand von Zirkon gegen Korrosion in Druckwasser bestimmen, werden im Einzelnen besprochen und dabei die Arbeiten diskutiert, die in den Vereinigten Staaten zur allgemeinen Annahme der Schwammlegierung Zircaloy 2 geführt haben. Ueberall wird mit Nachdruck auf die Wirkung hingewiesen, die Gas-Verunreinigung auf die Fabrikation, die physikalischen und mechanischen Eigenschaften und den Korrosions-Widerstand von Zirkon ausübt. Endlich werden auch die Arbeiten zur Entwicklung von Legierungen, die gegen Oxydation bei hohen Temperaturen widerstandsfähig und ferner kriechfest sind, kurz diskutiert, wobei auch die Wirkung behandelt wird, die Bestrahlung auf die mechanischen Eigenschaften und den Korrosionswiderstand hat.

Zirconio y sus Aleaciones

Se presentan en la forma de hojas de detalles, valores seleccionados para las propiedades físicas, químicas, mecánicas y nucleares de zirconio y sus aleaciones como componentes de envasamiento y núcleo en los reactores de gas presurizados y enfriados por agua, en relación a otros materiales de envasamiento de sección transversal de bajo apresado neutrónico. Los procedimientos principales para la retirada de hafnio han sido delineadas en forma tabular. Se discuten en detalle los factores que afectan la resistencia a la corrosión del zirconio en agua presurizada, juntamente con el trabajo que motivó la adopción de la aleación a base esponjosa, Zircaloy 2, en los Estados Unidos. Se hace hincapié en toda la extensión del artículo sobre el efecto de la contaminación de gases sobre la fabricación, las propiedades físicas y mecánicas y la resistencia a la corrosión del zirconio. También se discute brevemente el trabajo que se ha hecho con respecto a la evolución de la oxidación a alta temperatura y de aleaciones resistentes al escurrimiento, juntamente con el efecto de la irradiación sobre las propiedades mecánicas y la resistencia a la corrosión.

TABLE 15

Corrosion Resistance of Iodide Zirconium in Acid and Alkali Media. (Two weeks at 35°C) (38)

Medium	Low-Hf Zr		High-Hf Zr	Low-Hf Zr		
	(0.05% N_2)	(0.3% C)	(0.001% N_2) (0.022% C)	0.08% N_2	0.1% C	0.3% O_2
H_2SO_4 (conc.)	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble
H_2SO_4 (10%)	Wt. gain	Wt. gain	0.00011	0.000036	Wt. gain	0.00018
HCl (conc.)	0.021	0.24	0.024	0.3	0.017	0.012
HCl (10%)	Wt. gain	Wt. gain	0.000061	0.000097	0.000013	0.00026
HNO_3 (conc.)	Wt. gain	Wt. gain	0.0025	0.000012	0.00005	0.000036
HNO_3 (10%)	Wt. gain	Wt. gain	0.00005	No change	Wt. gain	No change
NaOH (50%)	Wt. gain	Wt. gain	0.0001	0.000061	0.000025	0.000074
NaOH (10%)	Wt. gain	Wt. gain	0.00005	Wt. gain	No change	0.00005
NaCl (20%)	Wt. gain	Wt. gain	0.000025	Wt. gain	Wt. gain	0.0001
HCl HNO_3 (1 : 4)	Slight	Slight	Slight	Slight	Slight	Slight
HCl H_2SO_4 (1 : 1)	0.000046	0.000016	0.00005	Wt. gain	0.00022	0.00025
H_2SO_4 HNO_3 (1 : 1)	0.16	0.15	0.25	0.01	0.12	0.058
Fuming HNO_3	Large wt. gain	Large wt gain	Large wt. gain	Wt. gain	Wt. gain	Large wt. gain
NH_3 (29.6%)	0.000025	Wt. gain	Wt. gain	Wt. gain	0.0009	Wt. gain

Corrosion rate is given in. per year.

the United Kingdom, with its history of gas-cooled reactors with fuel canned in magnesium or aluminium. However, the current interest in this country in the applications of nuclear power to marine propulsion may well stimulate zirconium development. Furthermore, if current British efforts to produce creep-resistant and oxidation-resistant zirconium alloys, suitable for service in carbon dioxide at temperatures around 500°C, are successful, these materials may well have a function as core materials in more advanced gas-cooled reactors.

TABLE 16

Tensile Properties of Irradiated Arc Melted Zirconium (ex Bureau of Mines) (34)

Prior cold work reduction in area (%)	0.2% yield strength (1,000 p.s.i.)	Ultimate strength (1,000 p.s.i.)	Elongation (% in 1 in.)	Reduction in area (%)	Modulus of elasticity (10^6 p.s.i.)
Preirradiation Control Material					
Annealed	34.5	64.1	33	51	14.7
Annealed	33.2	63.4	33	49	15.4
9.1	65.9	73.4	20	44	14.3
9.1	64.9	71.1	17	43	14.7
20.1	71.3	78.0	14	41	15.1
20.1	72.3	79.2	16	41	14.9
30.6	74.2	83.2	17	36	14.2
30.6	73.5	81.6	16	35	13.6
39.1	74.4	82.5	16	36	14.0
39.1	75.4	83.3	13	33	12.5
50.4	83.7	86.7	11	26	13.8
50.4	83.0	86.2	9	23	13.7
Exposed—5.7×10^{19} nvt Thermal at 50–60°C					
Annealed	51.3	70.6	25	45	13.4
Annealed	50.7	70.5	23	43	14.4
9.1	75.5	79.4	13	36	41.1
9.1	76.5	81.4	14	36	15.5
20.1	83.2	87.0	14	28	15.0
20.1	83.2	86.7	13	34	14.5
30.6	83.2	89.5	15	28	14.3
30.6	82.8	88.9	13	28	14.1
39.1	86.2	90.3	14	28	13.9
39.1	85.6	91.1	11	29	14.1
50.4	92.0	93.8	8	21	13.9
50.4	93.2	93.8	9	25	15.5
Exposed—1.5×10^{20} nvt Thermal at 50–60°C					
Annealed	51.3	67.1	23	41	14.0
9.1	76.8	79.2	16	36	12.2
20.1	83.8	85.7	21	35	14.3
30.6	85.4	88.9	10	23	13.4
39.1	86.4	89.4	*	29	15.2
50.4	93.7	95.3	8	23	13.9
Exposed—2.4×10^{20} nvt Thermal at 50–60°C					
Annealed	56.1	71.2	22	42	13.6
20.1	84.7	88.5	*	33	12.5
50.4	94.5	95.7	7	19	12.6
Exposed—1.5×10^{20} nvt Thermal and Annealed 100 h at 250°C in vacuo					
Annealed	48.2	64.8	*	43	13.7
9.1	73.8	78.1	18	40	12.9
20.1	76.5	80.1	20	34	14.2
30.6	77.8	84.1	*	33	14.0
39 1	79.5	86.5	12	27	13.4
50.4	84.7	89.0	10	26	12.8
Exposed—2.4×10^{20} nvt Thermal and Annealed 100 h at 300°C in vacuo					
Annealed	47.4	65.2	*	45	12.7
9.1	68.9	74.5	16	42	12.7
20.1	71.6	77 9	15	42	12.5
30.6	70.5	78.8	*	38	12.6
39.1	73.5	81.8	14	35	13.4
50.4	76.8	83.2	14	24	12.5
Exposed—2.4×10^{20} nvt Thermal and Annealed 160 h at 350°C in vacuo					
9.1	58.1	69.7	21	37	13.9
30.6	60.5	74.3	16	38	13.6
39.1	63.2	77.2	20	34	12.7

* Sample fractured outside or near gauge marks.

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France's New High-Flux Research Reactor

By **Gilbert B. Mélèse** (*Centre d'Etudes Nucleaires de Saclay ; at present Assistant Professor of Mechanical Engineering, Columbia University, New York*)

IN April, 1954, the Commissariat à l'Energie Atomique decided to build a research reactor with a neutron flux of 10^{14} n/cm²-sec, i.e., about ten times that of EL2, for high-flux testing and experimental facilities. Moderated and cooled by heavy water, the design originally envisaged natural uranium as fuel, in which case the thermal output would be in the region of 50 MW. Following a British offer to supply slightly enriched uranium, the same flux could be obtained with a thermal output of 15 MW which was, of course, preferable. At the time that EL3 was designed it was only possible to provide 1.35% enrichment; this is to be increased to 1.6% in the future.

Comparisons between the flux and power output of EL3 and other research reactors can be seen from Table 1. The flux is approximately three times greater than that of French power reactors of EDF1 type or the Marcoule G2 and G3.

High availability and safety were the dominating features in design, particularly the latter, since EL3 is located at the Saclay research centre, which is close to Paris. The reactor first diverged on July 4, 1957.

General Arrangement

From the aerial photograph in the heading and Fig. 1, it can be seen that the scheme consists of three main units. The reactor proper is located in the centre; to the left is the machine hall containing auxiliary plant. On the right is the fuel storage building which, like the reactor building, is an airtight cylindrical shell. The fuel storage and reactor buildings are connected by an airtight cylindrical steel tunnel. The main reactor building is 46 m (approx. 150 ft) in diameter, and the reactor shielding block, which takes the form of a 14-sided polygonal prism, is set slightly off-centre.

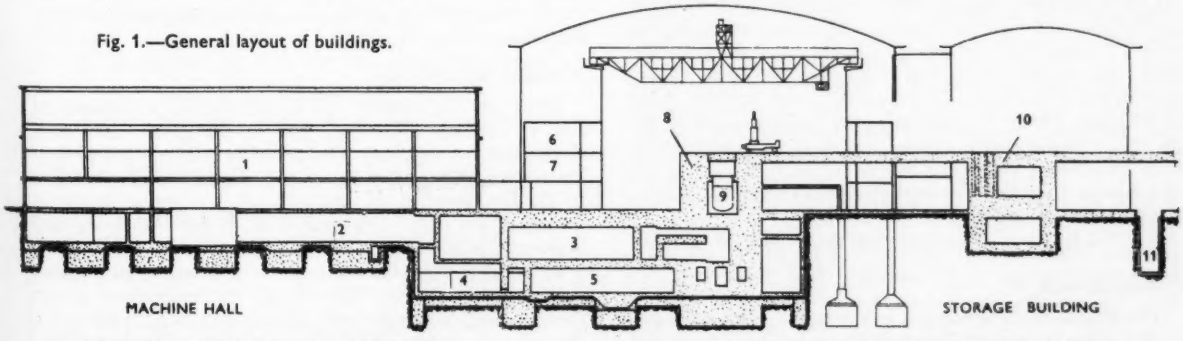
Core

The core consists of 99 fuel elements set in a hexagonal lattice with a pitch of 175 mm (6.9 in.). The fuel elements take the form of tubes of uranium alloy, probably molybdenum, with up to 1.5 wt.% foreign additions clad in aluminium with inside and outside diameters of 22 and 29 mm (0.865 and 1.14 in.) respectively, and 1.35 m (4 ft 6 in.) long. Fuel elements up to 40 mm (1.6 in.) external diameter can be accommodated if required.

The reactor in general is designed so that, if desired, the power rating can be increased to 30 MW.

The total weight of uranium in the core is approximately 4.5 tons. Control is by three safety rods, two regulating rods and six shim rods. The safety rods are boron carbide tubes of inside and outside diameter 28 and 36 mm (1.1 and 1.4 in.) respectively and 900 mm (approx. 3 ft) long; they are propelled by CO_2 under pressure. The regulating rods are of concentric aluminium tubes with boron carbide filling; the diameter is the same as the safety rods, but they are only 230 mm (9 in.) long. Shim rods are similar to the regulating rods, but have a length of 1.4 m (4 ft 7 in.); they have a value of 4% ΔK. Their speed is approx. 25 mm (1 in.)/sec, while the speed of the regulating rods is 18 mm (0.7 in.)/sec with a total travel of approximately 2 m

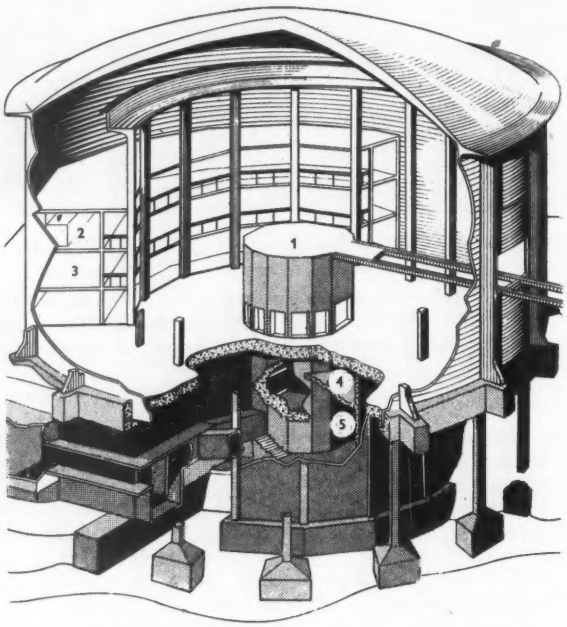
Fig. 1.—General layout of buildings.

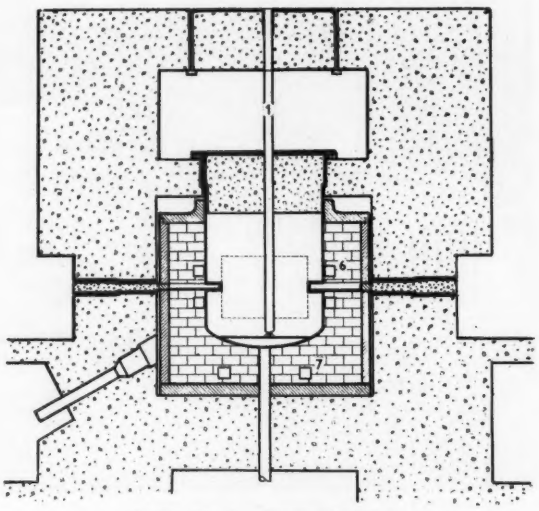


1. Machine Hall. 2. Pipe basement. 3. Heat exchanger. 4. Light water. 5. Heavy water. 6. Control room. 7. Laboratories. 8. Reactor. 9. Core vessel. 10. Dump. 11. Core pit.

TABLE 1. Design flux (thermal neutron) and start-up of reactors comparable with EL3

Country	Reactor	Design flux n/cm^2-sec	Power MW	Start-up
France	EL3	10^{14}	15	1957
Canada	NRX	6.8×10^{13}	40	1947
Canada	NRU	3×10^{14}	200	1957
Great Britain ..	DIDO	10^{14}	10	1956
Great Britain ..	PLUTO	10^{14}	10	1957
United States ..	MTR	5×10^{14}	40	1952
United States ..	ETR	10^{15}	175	1957
United States ..	ORR	1.3×10^{14}	20	1957
United States ..	WTR	10^{14}	20	1958?





(Left) Fig. 2.—Reactor building.
1. Reactor. 2. Control room. 3. Laboratories. 4. Cables and pipes. 5. Experimental auxiliaries.

(Above) Fig. 3.—Vertical section through reactor.

(6 ft 7 in.). The safety rods have a total run of 2.2 m (7 ft 0 in.) and their efficiency is said to be 75% after 0.1 sec.

The reactor operates in an atmosphere of helium.

Containment and Shielding

The core is contained in an aluminium tank 2.56 m (8 ft 5 in.) diameter, and 4 m (13 ft) high, with a wall thickness of 13 mm (0.51 in.) and a bottom thickness of 35 mm (1.4 in.). Around the core is a heavy-water reflector 400 mm (1 ft 3¼ in.) wide. The tank is surrounded by a graphite reflector with a minimum thickness of 600 mm (2 ft 0 in.) with a total weight of 80 tons. This is surrounded by a thermal shield of cast iron 200 mm (8 in.) thick, weighing 100 tons, which serves the dual purpose of shielding the concrete biological shield and acting as a separator for the inlet and outlet cooling air. The concrete biological shield, of density 4.2, is 7 m (23 ft) high and 2 m (6 ft 7 in.) thick, and weighs 1,650 tons. The tank lid, which can be seen in Fig. 3, is made of stainless steel, with 200 mm (8 in.) of lead and 1 m (3 ft 3 in.) of heavy concrete, and weighs 38 tons. Above this is a space 2 m (6 ft 7 in.) high which may be entered when the reactor is shut down. Above this there is a further concrete-filled steel-framed shield 3 m (10 ft) diameter and 1 m (3 ft 3 in.) high.

Fig. 2 shows a cut-away diagram of the reactor building.

Cooling System

The reactor is moderated by heavy water, which also acts as the primary coolant, being itself cooled by light water.

The heavy-water system can itself be considered as two systems, main and auxiliary. A simplified schematic diagram of the complete system is shown in Fig. 4.

Main D_2O System

The main coolant flow is from a bottom header in the tank around the fuel elements at a velocity of approximately 5.6 m/sec (18 ft 4 in.), and out to the main pumps and heat exchangers. The tank inlet and outlet temperatures are 40°C and 60°C (104°F and 140°F). There are three sets of pumps (main and auxiliary) and heat exchangers; one set acts as a stand-by.

The main pumps are of the canned motor type, lubricated with D_2O and are of the vertical centrifugal type with a capacity of 625 m^3/h (2,750 gal/min) against a head of 65 m (213 ft), the power consumption being 135 kW at 1,450 r.p.m.

The heat exchangers are of the horizontal counter-flow type with a heat-transfer capacity of 10 MW per unit. Temperature drop of the D_2O is 17°C for a 9°C rise in temperature of the H_2O secondary coolant, the respective flow being 500 and 1,000 m^3/h (2,200 and 4,400 gal/min). The heat exchangers are 7.16 m (23 ft. 6 in.) long, and all parts in contact with D_2O are of stainless steel with a maximum of 0.04% carbon. The main D_2O cooling system contains 20 m^3 (5,300 gal).

The auxiliary pumps are of two slightly different types, but both are centrifugal, sealed, and D_2O lubricated with a capacity of 90 m^3/h (396 gal/min) against a 5 m (16 ft 5 in.) head. These pumps are used for fuel element cooling when the reactor is shut down.

Auxiliary D_2O System

There are six storage tanks each having a capacity of 5 m^3 (1,320 gal). Three are used for dumping during shut-down, one for auxiliary storage while purging any part of the system, and another for extra D_2O used when alteration of the D_2O level in the reactor tank is being utilized as a means of control. The sixth tank is for recovering any accidental leakage.

In parallel with the main flow, there is a purification system with a flow of 300 l/h (1.3 gal/min) which passes through ion exchange resins (basic and acid types) at a temperature below 40°C, there being a separate heat exchanger for cooling purposes.

There is a burst can detector system which continuously samples each fuel channel with a by-pass flow of 330 l/h (1.45 gal/min) and the tank, with a by-pass flow of 700 l/h (3.1 gal/min). The monitoring of each sample takes 30 seconds per cell, and the normal signal from the tank

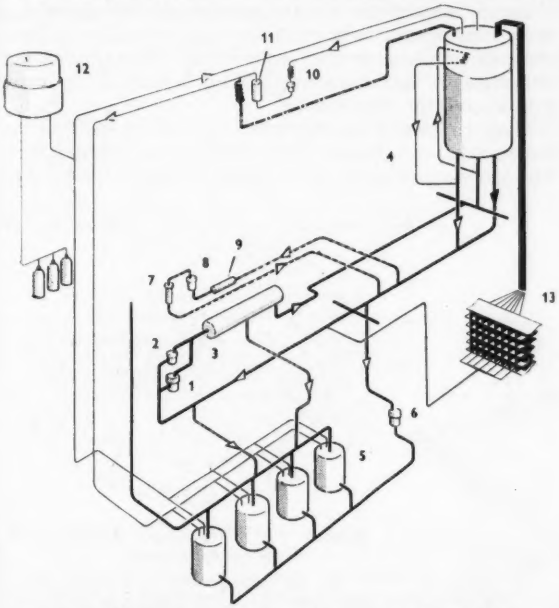


Fig. 4.—Schematic diagram of heavy water cooling system.
1. Main D_2O pump. 2. Auxiliary D_2O pump. 3. D_2O-H_2O heat exchanger. 4. D_2O tank lid cooling. 5. D_2O storage tanks. 6. D_2O feed pumps. 7. Ion exchange purifier. 8. Purification system pump. 9. Purification loop heat exchanger. 10. Recombination loop ventilator. 11. Recombination unit. 12. Helium tank. 13. Burst can detection system.

circuit is used as a background signal to be deducted from the signals obtained from the fuel channels.

Helium Circuit

As previously mentioned, the reactor and associated heavy-water circuits operate in a helium atmosphere, and the helium circuit is shown diagrammatically in Fig. 4, from which it can be seen that the helium flows continuously through the reactor tank and through a catalytic recombiner unit where deuterium and oxygen are recombined to heavy water; nitrogen is removed from the system by a cold trap. Helium is also injected into each sample of D_2O in the burst can detector system and then separated in a cyclone, carrying away the gaseous fission products for removal in purification units.

Light-water System

In addition to cooling the D_2O by the main heat exchangers, H_2O is used for cooling the irradiated fuel elements in the storage pits, and for secondary cooling of

TABLE 1. General particulars of EL3

Thermal power	15 MW
Maximum specific power rating	40 MW/ton of U
Max. thermal neutron flux	10^{14} n/cm²-sec
Heat flux	233 watts/cm² (7.4×10^5 B.t.u./ft²-h)
Maximum temperatures	
Uranium	450°C (840°F)
Can surface	
(smooth)	120°C (248°F)
(corrugated)	85°C (185°F)
Coolant inlet	40°C (104°F)
outlet	60°C (140°F)
Total heavy water in cooling system	20 m³ (5,300 gal)
Total weight of U	4.5 tons

General view of inside of reactor building in semi-completed stages.

the experimental loops. There are three main pumps with a flow rate of 1,500 m³/h (6,600 gal/min) against a 23 m (75 ft) head of water driven by motors with a load of 130 kW each.

The H_2O is itself cooled by a forced-draught cooler with two cells, each of which has a storage capacity of 310 m³ (815,000 gal) used as a stand-by. During periods of part load or shutdown auxiliary pumps are used; these are driven by motors rated at 15 kW.

Ventilation and Air Cooling

Air is used to cool the graphite reflector and the thermal shield in the reactor, and to condition and ventilate the air in the reactor and fuel storage buildings, which are both kept slightly below atmospheric pressure; the atmosphere surrounding the reactor tank is at a lower pressure still, so that any leakage will be inwards rather than outwards.

The air circuit is shown in Fig. 5 and is self-explanatory; the exhaust stack is 30 m (100 ft) high. The three fans have a combined capacity of 20,500 m³/h (12,000 ft³/min) against a head of 0.4 m (16 in.) w.g.

Fuel Element Handling

A bridge structure carrying a rail track runs from the top of the reactor into the fuel element storage building. The shielded flask unit has an electrical travel mechanism and a hand-operated traverse which permits the location of the flask over the fuel channel to an accuracy of ±0.5 mm. The flask itself is of stainless steel with 200 mm (8 in.) of lead shielding, its total weight being 27 tons. The grab mechanism for raising the fuel element is electromagnetically operated, and the flask incorporates closed-circuit helium cooling. The helium-cooled flask (Fig. 6) transports irradiated fuel elements to a point mid-way between the reactor and the fuel storage building, where it is deposited in an air-cooled chamber in an air-lock. An air-cooled coffin transports it from this point to the main block in the storage building (Fig. 7), where it is dumped into one of three pits. The first, or "ordinary," pit has a capacity of 108 elements; a second and smaller unit is provided for damaged elements. Both are light-water cooled. In addition, there are special channels for observation of fuel elements by periscope, television, or X-rays.

An interesting feature of the storage block is that it contains compartments in which experiments can be carried out on the irradiation of foodstuffs, by the gamma radiation from the spent fuel elements. Two compartments are provided, one being kept at normal temperature (37°C or 99°F) and one being refrigerated (−18°C or 0°F).

Another interesting feature is the provision of a place where the entire reactor core, complete with tank and lid,

can be dumped, if required. This is at the rear of the storage building (Fig. 7); the building is arranged with sliding panels in the wall to allow the passage of the core.

Instrumentation

There are, in all, three control panels, main, auxiliary, and an emergency panel for operation in case an excursion should have rendered evacuation of the building necessary. On the main panel, radiation intensity is continuously monitored in addition to fuel channel temperatures. Reactivity, reactor period, mass flow and pressures are also measured. Power measurements are measured in three ranges, 20 mW to 20 W, 20 W to 20 kW, and 20 kW to 20 MW. Automatic control by servo mechanism is provided to keep a constant power output.

Two types of safety chain are provided, there being 16 warning circuits operating on fuel element temperature rise and 12 scram circuits operating, for example, on the occurrence of a burst fuel element. Radiation monitors record dust, gas and gamma readings in various parts of the building.

Experimental Facilities

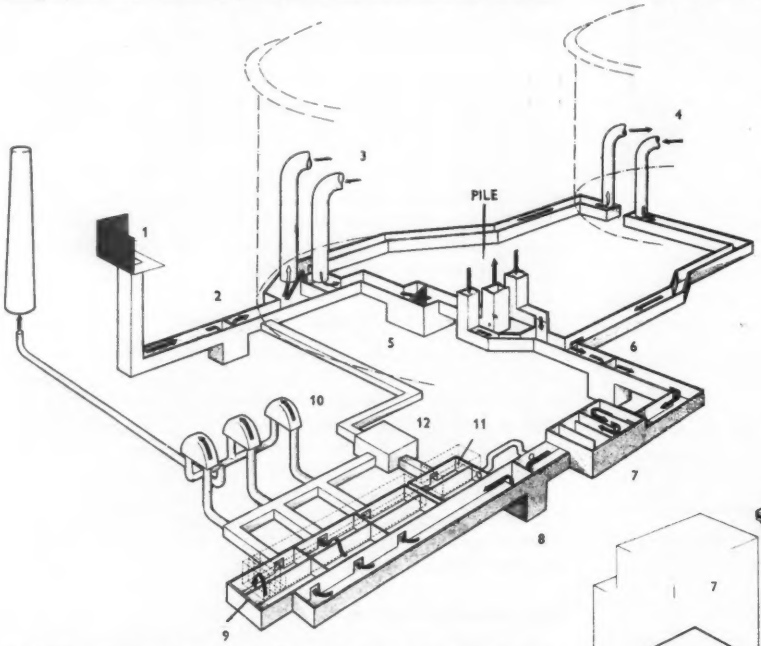
Some idea of the experimental facilities can be gathered from Figs. 3 and 8. There are 12 horizontal channels entering the tank radially; 10 are 150 mm (6 in.) diameter and the remaining two are 250 mm (10 in.). There are four straight-through tangential channels immediately outside the tank, at two levels, above and below the radial facilities. In addition, two " secant " channels are provided. There is also a thermal neutron column, 2 m (6 ft 6 in.) square.

The main vertical facility is a central one reaching almost to the bottom of the tank, which has an internal diameter of 0.182 m (7.3 in.); this is shown in Fig. 9. There are also a number of smaller vertical holes in both tank and graphite, including some of 300 mm (12 in.) diameter, and one of 30 mm (1.2 in.) diameter which is provided with a bismuth shield for irradiation without gamma.

Several fuel elements can be irradiated at the same time in the central channel. The coolant can be either carbon dioxide at 3 to 5 kg/cm^2 (42 to 71 p.s.i.) and a mass flow of 250 kg/h (9.2 lb/min) or helium, heavy water or an organic liquid such as terphenyl. Fuel elements of various diameters can be tested in two other high-flux vertical cells with D_2O cooling. Various types of cooling (high pressure and temperature) can be provided for the horizontal tangential channels, which have an average flux of 10^{13} n/cm^2-sec; creep experiments under irradiation are to be done in these channels with fuel elements under stress. Both loading and unloading of the above-mentioned cells have to be done with the reactor shut down.

Small samples of the fuel could be tested in some of the horizontal radial channels with a 10^{13} thermal neutron flux. The cooling problem is not as important as for the full-size experiments and a higher flux gradient along the channel can be tolerated.

The highest possible fast neutron flux is required for irradiation of reactor structural elements. Small samples. 20 cm (8 in.) long and 3 to 4 cm (1.2 to 1.6 in.) diameter will be irradiated in two vertical cells equipped with converters. Full-size elements could be introduced into a tubular converter in channel H11 (or H8) with a diameter of 250 mm (10 in.). These experiments will be done without any external connection. Similar experiments, but either with corrosion or at special (low) temperatures, could be done in one or two radial channels (with a high flux) and in one or two horizontal tangential channels (with dangerous

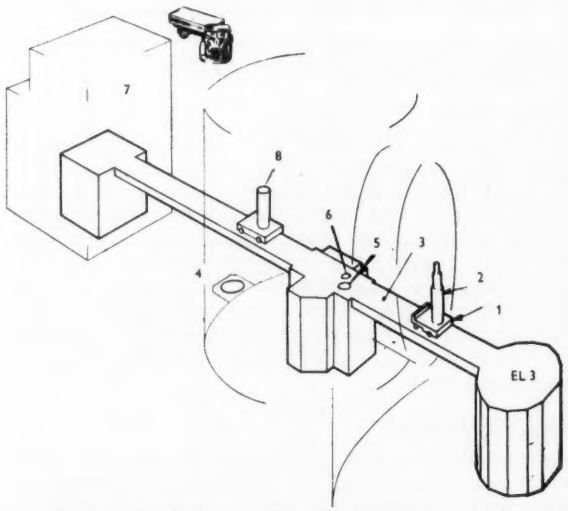


(Left) Fig. 5—Schematic diagram of ventilating system.

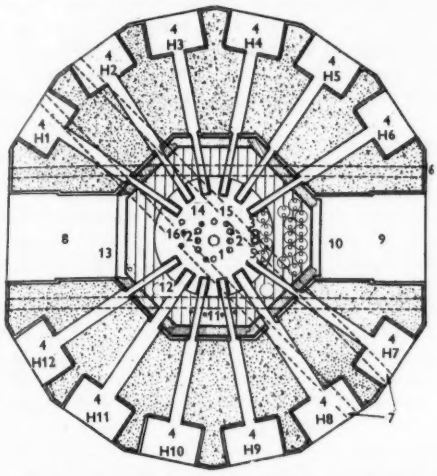
1. Filters. 2. Trap. 3. Reactor building inlet and outlet. 4. Fuel storage building inlet and outlet. 5. Filters. 6. Trap. 7. Settling chamber. 8. Trap. 9. Hot filters. 10. Fans. 11. Special hot filters. 12. Special decontamination equipment.

(Below) Fig. 6.—Schematic diagram of fuel handling system.

1. Main fuel handling trolley. 2. Helium-cooled spent fuel coffin. 3. Lockchamber. 4. Irradiated core pit. 5. Spent fuel element storage pit. 6. Fuel element observation channels. 7. Uranium recovery building. 8. Air-cooled coffin.



coolants, for instance). Irradiation in the two large diameter channels (300 mm or 12 in.) in the graphite reflector would necessitate a longer time due to the smaller flux (10^{10} to 10^{11} n/cm²-sec). A vertical channel with a bismuth screen permits an irradiation without gammas of small samples (up to 30 mm or 1.2 in. in diameter).



Radiation chemistry experiments could be done either in the radioisotopes channels or in the large diameter channels in the graphite; they could also be done in the same channels as the small structural samples irradiations.

Radioisotopes will be produced in several special cells: 8 channels in the heavy-water reflector, 120 cm (4 ft) long and 30 cm (1 ft) in diameter are in a flux of approximately 10^{13} n/cm²-sec, 200 isotopes containers can be irradiated in the 24 vertical channels in the graphite reflector. Four pneumatic vertical channels permit a fast automatic handling of rabbits, 100 mm (4 in.) long and 50 mm (2 in.) diameter.

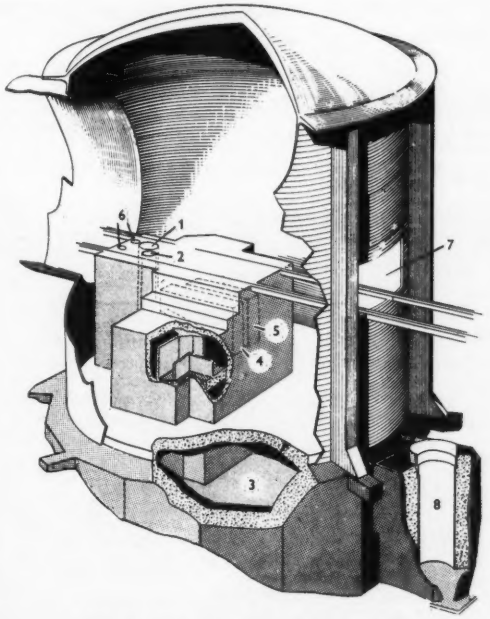
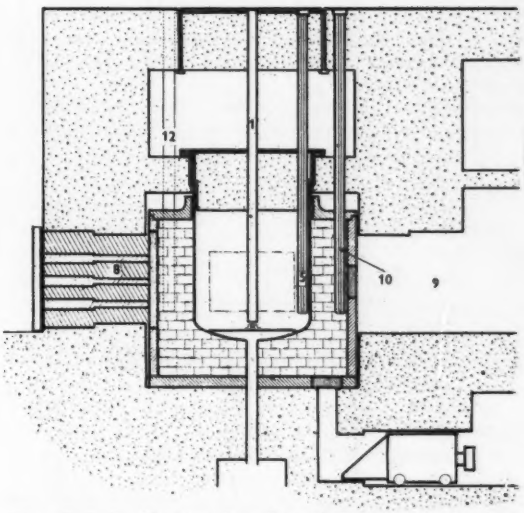


Fig. 7.—Fuel element storage building.

1. Ordinary spent elements. 2. Damaged element pit. 3. Water cooling equipment. 4, 5. Cold and warm food irradiation. 6. Channels for optical observation of spent fuel elements. 7. Removable panels (to let reactor core out). 8. Concrete pit for removed (irradiated) reactor core.

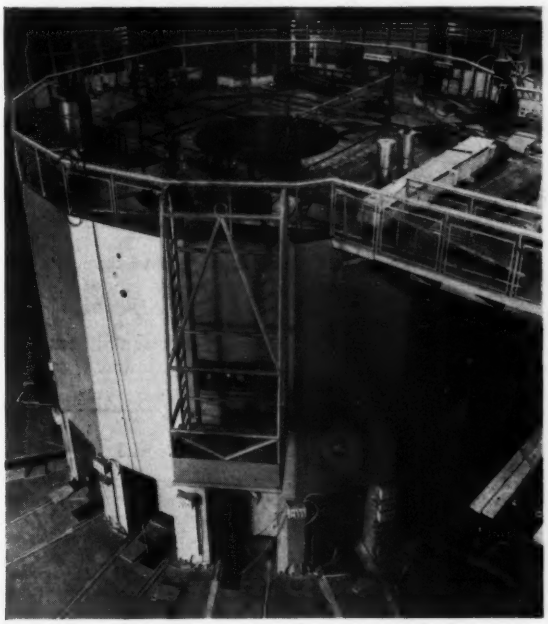


Figs. 8 & 9.—Horizontal and vertical sections, showing experimental facilities.

1. Vertical experimental hole—dia. 200 mm (8 in.). 2. Experimental cells for studying the behaviour of uranium bars. 3. Special cavities: rapid neutron converters. 4. Radial channels H1 to H12. 5. Eight vertical holes for isotope production. 6. Four tangential channels on two levels (above and below the radial channels). 7. Two secant channels 0.5 m (19 in.) from the ground. 8. Thermal column 2 m (6 ft 6 in.) square, filled with graphite blocks. 9. Large cavity. 10. Vertical holes in graphite. 11. Air-cooled vertical holes for rapid irradiation. 12. Vertical holes dia. 300 mm (12 in.). 13. Vertical hole dia. 30 mm (1.2 in.) entering a bismuth shield. 14. Safety bars. 15. Compensating bars. 16. Control bars.

In-pile Loops

When the fluid does not become very radioactive and does not carry any fissile product, one has only to connect the loop with a safety circuit of the reactor. This is the case when one uses either pressurized gases, or organic liquids, or else very pure light water. Leaks, pressure or temperature rises, corrosion products and reactor reactivity in case of a sudden coolant loss have to be carefully watched. When the fluid does not carry any fissile material



General view of reactor unit partly completed.

but becomes very active, the loop has to be shielded and made as short as possible. The horizontal channel H9 could be eventually used for such an experiment, with sodium for instance.

When the fluid carries fissile elements and becomes very radioactive, one must carefully watch for the eventuality of rupture, and criticality (either in pile or in various storage tanks) as well as for delayed neutrons activity. Such a loop will be installed in the H8 channel in order to study aqueous homogeneous reactors behaviour. Uranyl sulphate will be circulated in the loop up to a pressure of 70 kg/cm² (100 p.s.i.) at 230°C (446°F).

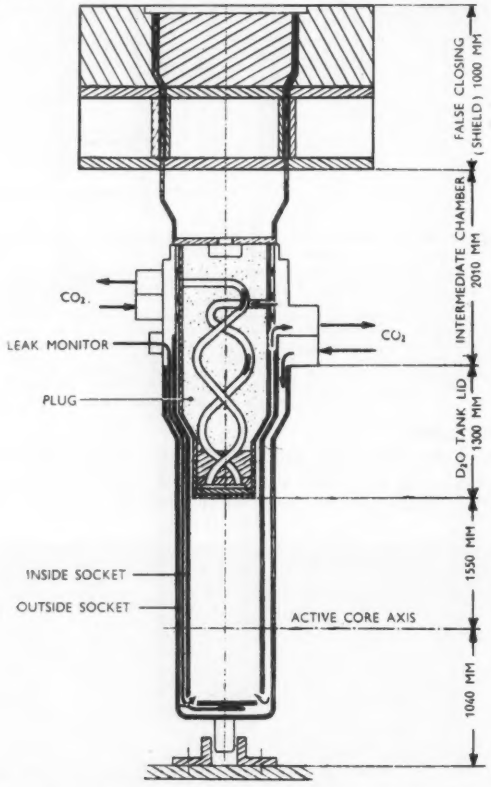


Fig. 10.—Arrangement of central experimental channel.

Physics and Biological Experiments

Various physics experiments with horizontal neutron beams are being planned for the radial channels: crystal spectrometer and very cold neutron experiments, as well as solid physics experiments (neutron diffraction) and time of flight measurements. The external side of the thermal column could be used as a good neutron plane source.

The large cavity in the concrete shield could be used for high-dose biological irradiations and for irradiation of large auxiliary equipment such as pumps, motors, etc. The two secant channels in the graphite reflector below the reactor tank will be used for biological studies: they open in two opposite special laboratories. The food irradiation experiments with the spent fuel elements have already been mentioned.

Other experiments such as creep measurements on fuel element under stress are carried out in the other Saclay research reactor EL2. This reactor is CO_2 cooled, heavy-water moderated and fuelled with natural uranium: the maximum flux is 10^{13} n/cm²-sec at 2,000 kW. Several loops are also installed in EL2: a high-temperature graphite CO_2 corrosion loop, a very low-temperature loop, an experimental high-pressure loop for burst can detection, etc. Together with the experiments to be done in EL3, they give a fairly good coverage of the useful in-pile possible studies. But since the large power reactors are going to need tens of thousands of fuel elements (of the order of 30,000 for one load of the Marcoule's G2 reactor), one would very much like to make statistical irradiation tests. A special materials testing reactor would be needed; it could now be fuelled with uranium at a much higher enrichment than EL3's. Such an enrichment would give a higher fast neutron flux available in a larger region; the experimental facilities could be more flexible if this enrichment made heavy water unnecessary.

Acknowledgments

The author wishes to acknowledge the very helpful advice and information provided by Mr. Jacques Robert, Deputy Director, Reactor Engineering Division, Commissariat à l'Energie Atomique. He is also grateful to Mr. Guilloux, Head, Documentation Branch at Saclay, for papers and photographs.

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3. de la Boulaye H. : Rapport sur l'exploitation d'EL3, Departement des Etudes de Piles, January 1957.
4. Raievski (M.V.) : Caractéristiques physiques de la pile a haut flux EL3, Noordwijk colloquium, September 1957.
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Le Réacteur Français d'Etudes à Flux Elevé EL3

Le réacteur français EL3 est devenu critique à Saclay le 4 Juillet 1957. Son but principal est d'assurer des facilités d'expérimentation de grandeur intégrale avec un flux à forte teneur en neutrons pour l'essai des éléments combustibles et constitutifs d'installations nucléaires. En outre, il y aura plusieurs boucles et facilités d'irradiation pour les biologistes, chimistes et physiciens. La facilité d'élément combustible irradié est contenue dans un édifice séparé étanche à l'air de manière identique à celle du réacteur lui-même.

Der französische Forschungs-Reaktor EL3 mit hohem Durchfluss

Der französische Reaktor EL3 in Saclay kam in das kritische Stadium am 4. Juli 1957. Sein Hauptzweck ist experimentelle Gelegenheit mit hohem Neutronenfluss in voller Stärke zur Prüfung von Brennstoff-Elementen und anderen Bauteilen von Atom-Werken zu schaffen. Des Weiteren sind mehrere Schleifenanlagen und Bestrahlungsmöglichkeiten für Biologen, Chemiker und Physiker vorgesehen. Die Prüfung bestrahlter Brennstoff-Elemente ist durch ein gesondert gehaltenes luftdichtes Gebäude möglich gemacht, das in ähnlicher Weise wie der Reaktor selbst gestaltet ist.

El Reactor Francés de Investigación EL3 de Alto Flujo

El reactor francés EL3 se volvió crítico el 4 de julio de 1957 en Saclay. Su objeto principal es el de ofrecer facilidades de experimentación en escala amplia con un alto flujo neutrónico para ensayar elementos de combustible y componentes de instalaciones nucleares. Además, habrá varios lazos y facilidades de irradiación para biólogos, químicos y físicos. La facilidad del elemento de combustible irradiado se halla contenido en un edifico separado hermético de una manera similar al propio reactor.

"459"

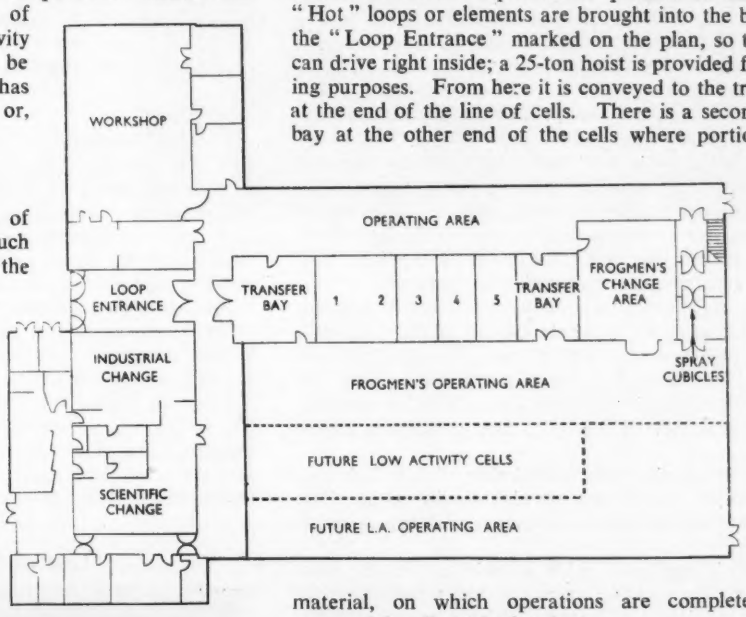
Harwell's New High-activity Handling Building

SAFETY and flexibility in operation are the distinguishing design features of the new high-activity materials handling building recently completed at A.E.R.E. Harwell.

Designed as a "workshop" facility for the dismantling of irradiated components and loops from DIDO and PLUTO, the unit is capable of handling components with activity levels up to 10^5c—believed to be the highest for which provision has so far been made in Britain or, indeed, in Europe.

General Layout

A careful study of the plan of building "459" shows how much forethought has been applied in the design stage. The building is roughly "T"-shaped, the crossbar of the T containing what might be termed the "service" departments, such as changing rooms, stores, offices, messroom and workshop, while the leg of the T forms the actual "operations" portion of the building. "Hot" loops or elements are brought into the building by the "Loop Entrance" marked on the plan, so that lorries can drive right inside; a 25-ton hoist is provided for unloading purposes. From here it is conveyed to the transfer bay at the end of the line of cells. There is a second transfer bay at the other end of the cells where portions of the material, on which operations are complete, can be removed for dispatch elsewhere.



(Top, right) Working face of Cells.

(Right) Block plan of Building "459."

(Below) Cell interior showing remote operation of metrology apparatus.

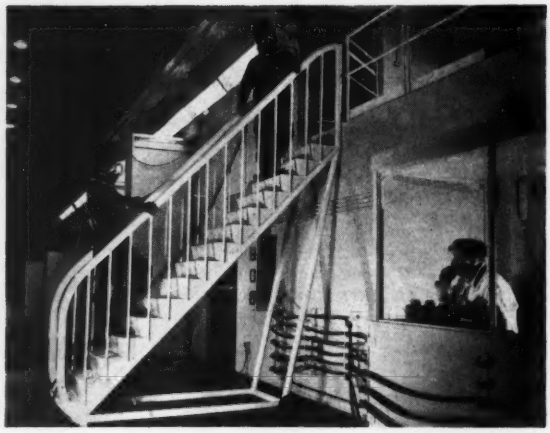
At some future date, it is intended to construct a line of medium-activity cells which will be arranged back-to-back with the high-activity cells. The operating areas will be on the outside of the enclosure thus formed, i.e., against the opposite walls of the main building, with the service or frogmen's area between the two rows of cells. At the moment, of course, this area is blanked off and access to the rear of the cells can only be had through the frogmen's entrance.

Cell Construction

The five high-activity cells are planned on an 8-ft module. At present there is no partition wall between cells 1 and 2 so that there are, in effect, one 16-ft and three 8-ft cells in succession.

After a thorough investigation into the relative economics of ordinary and high-density concrete, it was decided to use ordinary aggregate for the side walls, and they are, in consequence, 5 ft 6 in. thick. A further advantage of natural concrete was that it facilitated the housing of the zinc bromide windows.

(Above) Decontaminating a manipulator.



(Right) Inside the maintenance area, showing ladder to filter platform, and frogmen's control room.

The partition walls are made of steel tanks filled with steel-shot concrete of density 350 lb/cu. ft, the thickness being 2 ft. The lower portion of the wall is made in two sections, the rear section being arranged to form a sliding door which can be withdrawn into the maintenance area. The other portion of the wall can be removed (using jacks) if necessary so that, if required, the entire range could form one cell 40 ft long.

The line of cells is equipped with a 1½-ton remote-controlled overhead travelling crane, a 5-ton self-propelled bogie and a power-operated manipulator. In order to allow the passage of the crane or power manipulator from one cell to another, the upper portion of the partition wall is built as a rising door, hydraulically operated.

Normally, transfer of material from one cell to another is via a shielded flask—which is located in the frogmen's service area and passes material into and out of the cells via plug doors. The doors themselves can be racked right out into the service area, to allow maintenance access by frogmen, when required. The service area contains a 10-ton crane.

Each cell has a zinc bromide window, 5 ft × 3 ft and 5 ft 6 in. thick, backed up by high-density glass. The zinc bromide tanks are made in " Fibreglass " bonded with epoxide resin.

Each cell is equipped with a pair of master-slave manipulators. In addition, there is the power-operated manipulator previously referred to, which is common to the line of cells. This unit, remotely operated, has elbow and wrist movements; it is capable of a direct vertical lift of 700 lb or, when angled, of supporting a torque of 150 lb-ft at the elbow and shoulder joints. The grip of the fingers can be as high as 200 lb.

While it is quite possible that the " programme " may be varied, it is normally intended that the large first cell (1 and 2) should be used for loop reception and coarse cutting (making, for example, two circumferential and two longitudinal cuts for opening up a loop). Cell 3 is scheduled for fine machining, 4 for metrology and 5 for physical testing. In order to ensure flexibility and smooth working, a considerable amount of pre-planning is foreseen on each different job and the necessary machine groups will be " pre-fabricated " in the workshops and thoroughly tested under inactive conditions so that they can be rapidly installed, and obviate the considerable delays that occasionally occur when modifications have to be made on gear that is already in active surroundings.

Very careful attention has been paid to the balancing of ventilation throughout the building, and to the filtering of the air at both intake and exhaust. In order to ensure that the flow of air is always from " clean " to " dirty " areas, the cells themselves are maintained at a negative pressure of 0.7 in. w.g. compared with atmospheric, and the maintenance area at 0.3 in. w.g.

Maintenance

The decontamination of cells by remote means is a slow and laborious operation, and it is expected that this will be carried out down to residual levels, so that it can be completed by maintenance men in full protective clothing.

A most comprehensive series of safety precautions ensure that this can be carried out without risk. Frogmen wearing thick rubber suits and helmets are supervised from a control room that has a window giving a view of the entire maintenance area and, the chargeman has complete control over each man, even to paying out his air hose, which is remote-controlled by an air motor.

Frogmen leaving the area do so via a series of cubicles for surface decontamination; these cubicles, which are separated by glass doors, are fitted with sprays for detergent and clean water. The man who finally removes their helmets himself wears an air hood and gloves.

List of Contractors

ANDREW MACHINE CONSTRUCTION CO. LTD., Woodbank Works, Stockport
Ventilation plant.

JOHN BARNSLEY AND SON LTD., Netherton, Nr. Dudley, Worcester
10-ton and 1½-ton electric cranes.

CHANCE-PILKINGTON OPTICAL WORKS, St. Asaphs, Flint
High-density glass.

CHATWOOD MILNER LTD., Engineering Division, Shrewsbury, Shropshire
Handling bogies for 25-ton transport flask and 8-ton transport flask and cradle for active area.

W. E. CHIVERS AND SONS, Devizes
All civil engineering construction.

CLECO ELECTRIC INDUSTRIES LTD., Foundry Square, Leicester
Remote-controlled electrically driven bogie.

FELLOWS BROS. LTD., Clyde Works, Cradley Heath, Birmingham
25-ton crane.

GENERAL MILLS INC., Minneapolis, U.S.A.
Power manipulator (mechanical arm manipulator).

MATTHEW HALL AND CO. LTD., Matthew Hall House, Dorset Square, London, N.W.1
Cell steelwork, cell doors and general piped services.

MENDIP CHEMICAL ENGINEERING LTD., Feltham Road, Ashford, Middlesex
Fibreglass window tanks.

POWERHOUSE COMPONENTS LTD., Wayne House, Regent Street, Nottingham
Cable reel for power manipulator and 1½-ton cell crane.

REID AND PARTNERS LTD., 28-32 Hatfields, Stainford Street, S.E.1
Electrical services.

SAVAGE AND PARSONS LTD., Watford By-pass, Watford
Master slave manipulators.

GEORGE VERNON SALES LTD., 2 Baldock Road, Stotfold, Arlesley, Beds
Metrology equipment.

VOKES LTD., Henley Park, Guildford, Surrey
Air filtration, building and cells.

WESTERN DETAIL MANUFACTURE LTD., Staple Hill, Bristol
Cell benches and equipment.

Zirconium Production

Rapid Creep-Strain Testing Methods Used in Wm. Jessop's Research Laboratories

THE production of zirconium, to which reference is made elsewhere in this issue, has previously been described (*Nuclear Engineering*, June, 1956, p. 111) and a brief description of the arc furnace appeared in the September, 1956, issue, p. 254.

Both zirconium and titanium are produced by the consumable-electrode process at the Brightside works of William Jessop and Sons Ltd., and at their research laboratories at Whiston Grange, near Sheffield.

The company has had a considerable reputation in the steel industry since 1774. The research department began to grow out of routine investigation work in the early 1930s and additional impetus was given by the entry of the company into the field of high-temperature alloys. The present premises at Whiston Grange were adapted in 1950 as a centre for long-term research work, and some 50 of the company's total of nearly 200 research workers—representing nearly 6% of the total employees—are accommodated here. A certain amount of zirconium is actually produced on a small scale, but the majority of the production takes place at the Brightside works.

Part of the creep-testing laboratories with standard tensile machines.

The Refining Process

Both zirconium and titanium are produced by very similar processes. The metallic sponge (hafnium-free in the case of zirconium) is first compacted by a hydraulic press in the form of a semi-octagonal block, two such blocks being welded together to form an octagonal prism. These are then welded end-to-end to form an octagonal electrode, which is then melted under a vacuum. It is usual to repeat the process using the product of the first melt as the electrode for the second melt.

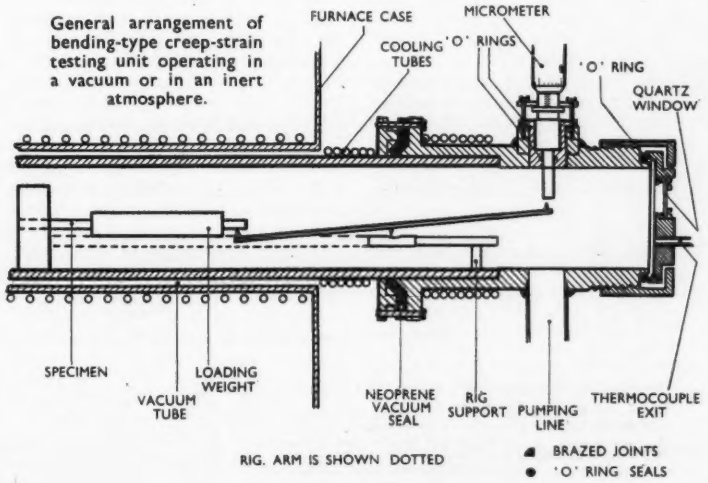
Creep Testing

With the very wide range of alloys manufactured, particularly for high-temperature applications, it will be realized that creep testing forms a very important part of the work carried out. Jessop's have what is said to be the largest installation of creep-testing units in any industrial establishment in Great Britain, over 200 units being constantly in use.

Creep testing is, however, essentially a long-term project and the actual measurement of the increase in length under tensile stress is by no means an easy matter. It was decided some two or three years ago that it would be helpful to devise some form of test that would give comparatively rapid indication of creep characteristics for rapid comparison of alloys under development. The method evolved consists in measuring the creep of heated specimens subjected to bending stresses, and the apparatus is exceedingly simple. The test specimen is a small cylindrical bar, no intricate shaping being required; one end is slipped into a hole in a support block and the other is loaded with a weighted lever. The whole is then placed in a tubular furnace, two units being often used back-to-back in a double-ended furnace. The deflection of the specimen, suitably magnified by a lever system, can be read at any time by means of a micrometer head, the instant of contact of the measuring point being indicated by the lighting of a neon lamp.

In the case of zirconium, testing is usually required either in a vacuum or in an inert atmosphere. The accompanying illustration shows a unit developed for this service, and shows how easily this apparatus can be modified for vacuum operation.

General arrangement of bending-type creep-strain testing unit operating in a vacuum or in an inert atmosphere.



Technical Papers and Publications

I.E.E. (Measurement and Control Section, in conjunction with the B.N.E.C.)

The Application of Digital Computers to Nuclear Reactor Design. By J. Howlett, B.Sc., Ph.D., A.M.I.E.E. (A.E.R.E. Harwell).

Reactor design necessitates a considerably greater amount of computation than any other engineering work. It is necessary to examine the design in great detail to ensure optimization of an exceedingly costly project, and the possible consequences of a design error are serious. The nuclear events are complex and the equations cannot be simply handled, since the basic data is complicated by being largely dependent on energy levels, not easy to represent by simple mathematical forms. In addition, it is essential that information obtained from the analysis of an initial exponential experiment should be rapidly available.

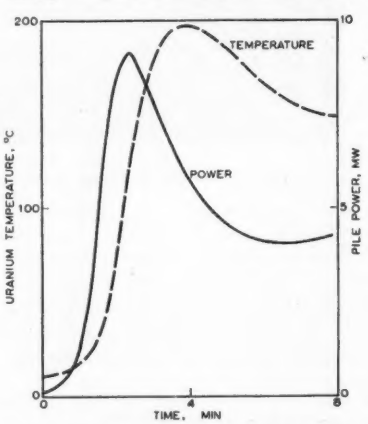
Taking into account the number of times that computations must be performed, with parameters modified from the results obtained, there is an overwhelming case for a fast flexible machine. Without it, a design team must carry out its work with a less detailed survey than is preferable, and using assumptions and simplified methods known to be of lower accuracy.

The paper briefly discussed the two broad classes of method involved in neutron transport calculations, the discrete particle (Monte Carlo) method, and the Boltzmann transport equation. A number of examples of machine applications reviewed included the calculation of the thermal utilization factor of a lattice by the spherical harmonics method; the direct solution of the two-group diffusion equations for a cylindrical reactor and the calculations of resonance escape probability for a graphite-uranium lattice by Monte Carlo methods. Particular emphasis was laid on the necessity of considering the machine's capabilities first of all; it was not sufficient merely to mechanize a problem without considering the machine, which might be suited to methods not dreamed of for hand computation.

Reviewing the question of future developments the author pointed out that the Mark 1* computer with a speed of about 500 operations/sec. was about at its limit in the solution of the two-dimensional criticality problem; machine runs of two hours per solution became uncomfortably long when evaluating a survey of 10-20 solutions. The Mercury and the 704 were adequate, since their speeds were 10-20 times this. As reactor design progressed it would be necessary to have faster machines, and speeds of about 10^5 operations/sec. with a fast store for 10^6 numbers would be required. Two examples of U.S. computers under construction were quoted, the second, due in 1960, having 10^6 operations/sec. It was interesting to note that computer speeds were approaching finality—1 microsec. for a complete multiplication required an operating frequency of up to 200 Mc/s., and the time taken for the pulses to travel round the computer was beginning to limit its size; hence the name for the computer in question: "Stretch."

Temperature Transients in Gas-cooled Thermal Reactors. By J. H. Bowen, B.Sc., A.M.I.E.E. (U.K.A.E.A.I.G.) and E. F. O. Masters, B.Sc., A.M.I.E.E. (Preece Cardew and Rider.)

The limiting feature in the operation of a gas-cooled reactor is the temperature of the fuel element can. Economy demands that this temperature should be as high as practicable; possible damage imposes an upper limit which must not be exceeded. Economic design necessitates a knowledge of the extent of transient temperature rise (due to abnormal conditions) that must be allowed for in determining the normal operating temperature. This paper, which is in many ways allied to the previous (computer) paper, examines various problems of temperature transients in gas-cooled reactors, including step changes in reactivity, i.e., abrupt increases such as are caused by sudden movements of the control rods, with constant cooling; gradual changes, i.e., at a constant rate of increase such as at start-up; and coolant failure due to loss of gas or blower outage. It is shown how, by making certain assumptions to simplify the problem, graphical and analytical methods can be used for the determination of transient increases. The results obtained are found to compare closely with those obtained from an analogue computer.



Power and temperature transients of BEPO, following 0.2% excess reactivity, with low starting power.

Boron Trifluoride Proportional Counters. By W. Abson, B.Sc., A.M.I.E.E., P. G. Salmon, S. Pyrah (A.E.R.E. Harwell).

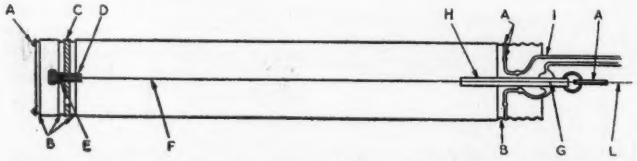
Boron trifluoride proportional counters have a wide application for detection of thermal and epithermal neutrons, and may be used in the form of multiple arrays of large counters for high-efficiency detection (i.e., in time-of-flight spectrometers) or, at the other end of the scale, as very small units for flux distribution measurements.

The paper gives an account of improved designs and manufacturing techniques introduced to overcome difficulties with earlier units, which included unsatisfactory vacuum-tightness due to porosity and age-cracking. These could be overcome by tinning the outer surface, but this imposed an upper limit of about 100°C on the temperature during outgassing, and required long pumping periods and an ageing period with a temporary gas filling, ageing periods of up to three months being necessary for large counters. Outgassing of the new design of counter can be carried out at 400°C, thus giving good shelf-life without requiring long periods of ageing.

The new design utilizes a body of thin-walled copper tube, induction brazing being used in the construction. The spring-loaded control anode wire is supported by a quartz disc at one end and by a glass-metal seal at the other end which also acts as a connection.

The new design has been standardized in ¼ in., 1 in. and 2 in. diameter tubes, the respective wall thicknesses 0.015 in., 0.02 in. and 0.025in., the corresponding anode wire diameters being 0.001 in., 0.002 in. and 0.004 in.

The most elaborate precautions are taken to ensure the purity of the boron trifluoride gas. Generation is from a



General construction of 1 in. cathode-diameter BF_3 proportional counter.

A, Hard-soldered at these four points using silver/copper eutectic solder of melting point 778° C; B, Swages rolled into body for location of end-caps and for locking quartz disc; C, Quartz disc; D, Tube for end termination, sprung-loaded; E, Inconel coil spring; F, Tungsten or Inconel wire anode; G, Spot weld to anode wire; H, Guard-ring electrode; I, Glass/metal seal; L, Nickel wire.

boron trifluoride/calcium fluoride complex prepared by heating calcium fluoride in a solution of BF_3 in ether and distilling off the ether. It is then passed through cold traps to remove water vapour and through sodium fluoride to remove hydrofluoric acid, frozen in a further cold trap, then allowed to vaporize and transferred to glass storage vessels, which have been previously outgassed.

Discrimination between neutrons and γ radiation is quite good. For a 1 in. counter, filled to a pressure of 40 cm Hg, the average pulse height due to γ radiation is approximately one-hundredth of the maximum neutron pulse height. When the mean interval between γ pulses is less than the resolving time of the counter and its associated circuits, pulse build-up will occur and the counts due to γ radiation will be registered at higher discriminator-bias levels. It is stated that they can be used to distinguish between neutrons and γ radiation at dose rates of 100-200 rad/h.

Operation is satisfactory up to temperatures of 100°C and counters have been operated at this temperature for three months continuously without appreciable change in characteristics, although at 150°C a change can be observed after a few weeks. It is stated that a 1 in. diameter counter 6 in. long can be used for 10^{11} counts before significant deterioration of counting characteristics occurs.

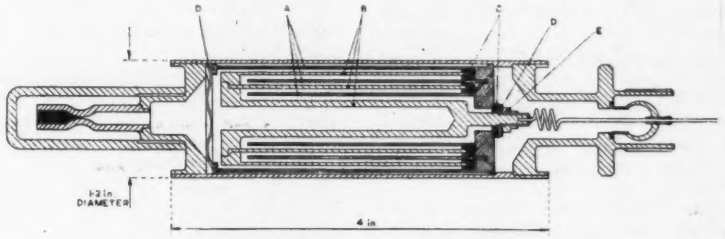
Acknowledgment is made to collaboration from 20th Century Electronics Ltd.

The Design, Performance and Use of Fission Counters. By W. Abson, B.Sc., A.M.I.E.E., P. G. Salmon, and S. Pyrah (A.E.R.E. Harwell).

The counters described in this paper were developed for measurements in reactor core assemblies, where the outstanding requirement is ruggedness of design.

Fission counters, which detect high-energy ionizing particles, by their action on a thin layer of fissile material in an ionization chamber, have a considerably higher degree of discrimination between neutrons and gamma rays than do the boron trifluoride counters reviewed in the previous paper; particularly at high count rates. It is possible, for example, to operate a fission counter with a cathode area of some 100 sq. cm at γ levels of 10^5 rad/h and still obtain discrimination, whereas the limit for a BF_3 counter would be of the order of 100 rad/h. Many fission counters can operate in temperatures up to 200°C, and developments are taking place for operation up to 500°C. For slow neutron detection and maximum sensitivity the coating is usually of U^{235}; for fast neutrons U^{238} or Th^{232}. A U^{235} coating of, say, 1 mg/cm², can be deposited by a solution of uranyl nitrate in alcohol and acetone, afterwards baking at 600°C to burn off the nitrocellulose binding agent and reduce the uranyl nitrate to U_3O_8 which remains as a tough adherent layer. It is not possible to deposit more than 0.1 mg/cm² per coating if the layer is to adhere, and the required thickness must be obtained by repetition of the process.

The illustration shows a cross-section of a typical medium size multiple plate counter, the A.E.R.E. type B165, with a cathode area of 165 cm². The length of the coated area is approximately 2 in., and the assembly is contained within a cylindrical envelope of 1.2 in. diameter. The electrodes and outer tube are all made from stainless steel of wall thickness 0.02 in. Five of the cathode surfaces may be coated (the inside and outside of two cylinders and the inside surface of the outer one) giving a total area of 165 cm². After the coating process the cathode and anode coaxial cylinders are fitted together as a complete assembly, the various parts being located with respect to one another by means of grooves in the surface of the quartz insulators. A Nimonic-alloy spring D is used under the fixing nut E to take up any relative expansions which may occur during outgassing processes or operation of the counter at high temperatures. The assembly of the outer envelope is completed except for the welding of the bottom end-cap; the electrode assembly is then fitted into the envelope, the anode-lead wire being threaded through the central tube of the glass/metal (or ceramic/metal) seal. The remaining operations before pumping and filling are then limited to the welding of the end-cap and the brazing of the anode wire to the central tube of the glass/metal seal. It is desirable to arrange the design of fission counters so that final assembly operations are as simple as possible, since in cases where the coating has a high specific α-activity it is necessary to do the whole of this work under dry-box conditions.



Multiple-plate fission counter type B165.
A Coated cathode tubes. B Anode. C Quartz insulators. D Nimonic springs. E Fixing nut for anode/cathode assembly.

Fission counters at present developed range from large high-sensitivity units with a cathode area of 1,500 cm² to flux-scanning counters less than 3 in. long which can be used inside a ¼ in. pipe.

A further property of the fission counter is its long life, counters of the size of B165 having been operated for about 1.5×10^{12} counts without change in characteristics.

CORRESPONDENCE

The Price of Beryllium

Dear Sir,

In your January issue Mr. L. Ross Williams, in an otherwise excellent article on "The Metallurgy of Beryllium," makes a startling assertion. He says: "Recent large orders for the metal placed by U.S.A.E.C. have been placed at a price (cast metal) equivalent to that paid a few years ago for the ore alone." I would suggest that if the economics of the use of beryllium in reactors are being worked out on this basis the authority is in for some rude shocks.

A price of about 245s. per unit BeO contained in ore can be considered representative for "a few years ago." This is roughly equivalent to 11s. per lb. of oxide or 30s. per lb. of beryllium contained and is rather less than one-tenth of the price settled between the largest American producers and U.S.A.E.C. for five-year procurement agreements at very high levels of output from plants to which exceedingly favourable amortization conditions apply and from processes on which most of the development work has already been paid for under previous Government contracts framed in generous terms. Yours faithfully,

Murex, Ltd., *P. S. Bryant.*
Rainham, Essex.

Dear Sir,

Thank you for your letter of the 9th inst. enclosing Mr. Bryant's comments regarding the statement of the present-day economics of beryllium metal as published recently in *Nuclear Engineering*. The intention of the phrase was, of course, to draw attention to the significant drop in price of beryllium metal during the past few years.

The statement as made is factually wrong and the word "ore" should be replaced by "raw material" (pure BeO). I would suggest that an amended form of the statement could read as follows:—

"Recent large orders for the metal placed by U.S.A.E.C. have been based on price (cast metal) of the same order as that paid a few years ago for beryllium in the form of pure nuclear grade oxide."

We are very grateful to Mr. Bryant for pointing out the error. I feel this re-wording, together with the statement on page 1 where the price of the metal is given, will give the readers a full picture of the economics of beryllium for reactor use.

Yours faithfully,

U.K.A.E.A., *L. R. Williams.*
R. and D. Branch,
Springfields.

NEW BOOKS

Elementary Nuclear Physics. By W. K. Mansfield, B.Sc. (60 pp. 38 illus. Temple Press, 10s. 6d. net.)

No. 1 of the *Nuclear Engineering* Monograph series, this book is intended for those who are not themselves physicists, but require the rudiments of nuclear physics without a depth of treatment which might prove embarrassing. It should be particularly attractive to students, or to those who are, for example, considering the applications of isotopes.

The author, who is Lecturer in the nuclear engineering laboratory of Queen Mary College, has based this monograph on his own lectures and has aimed —remarkably successfully in our opinion —at the H.N.C. level. Chapters are: The Atomic Theory of Matter; The Nucleus; Radioactivity; Neutron Physics; Interaction of Nuclear Radiation with Matter; Detection of Nuclear Radiation. There are a useful table of notation, a table of the properties of elements used in nuclear engineering, and an index.

Nuclear Reactor Theory. By J. J. Syrett, B.A. (80 pp. 24 illus. Temple Press, 12s. 6d. net.)

No. 2 in the *Nuclear Engineering* Monograph series, this book is aimed at giving some grounding in the application of physics to reactor design, for students and engineers who are not themselves physicists. The author is a member of the Reactor Division of A.E.R.E. and has based his book on a course given to engineers and physicists arranged by the University of Manchester (Mechanical Engineering Department). An idea of the contents is given by the chapter headings: Nuclear Chain Reactions; Diffusion of Thermal Neutrons; Slowing down of Neutrons; Calculation of Critical Size; Lattice Calculations; Reactor Operation at Power; Types of Reactor and Fuel Cycles. Appendices cover notation, the averaging of reactor cross-sections, epithermal absorption in a thermal reactor. A useful bibliography is included for each chapter.

Reactor Heat Transfer. By W. B. Hall, B.Sc.(Eng.), A.M.I.Mech.E. (68 pp. 15 illus. Temple Press, 10s. 6d. net.)

Like the other volumes in the *Nuclear Engineering* Monographs series, of which this is No. 3, the aim throughout has been to give engineers, physicists, and students, some grounding in a subject which is not their own, but the treatment differs from that adopted in the two previous books in the series. The author, who is Research Manager at the Windscale R and D Labs of the U.K.A.E.A. I.G., has not divided the book into short chapters but has (in the manner of Julius Caesar with All Gaul) divided it firmly into three parts, which he has entitled Fundamentals of Convection Heat Transfer; Heat Transfer in the Reactor Core; Miscellaneous Topics. Part One, which is entirely devoted to the fundamentals of heat transfer by convection, might be summed up as Theory; Part Two, which is devoted to the application of heat transfer data to reactor design, might be called Practice.

A deep understanding of human weakness is shown in the implied permission (given in the preface) to start half-way for those who are familiar with " or are prepared to accept " the basic data.

The final section is devoted to such miscellaneous matters as liquid metals, temperature gradients along fins, comparison between liquid and gaseous coolants. Bibliography and an index are included.

Problems in Nuclear Engineering (Vol. I) and **Reactor Operational Problems** (Vol. II) of papers from the First Nuclear Engineering and Science Congress, Cleveland, Ohio, December, 1955. (Edited by D. J. Hughes, Stuart McLain and Clark Williams. 365 and 278 pp. respectively. £6 per vol. or £10 the set.)

These two volumes contain a total of 88 papers selected from 358 presented at this Congress which included more engineering type papers, with a wider scope than those presented at Geneva. The papers in these two volumes are representative of this approach.

Vol. I is divided into four sections. Section 1 (Site Selection, Safety and Economics) contains 10 papers embracing the first two titles (but little on Economics) in connection with water and liquid metal cooled reactors. The site evaluation method leading to the selection of the Savannah River site is interesting.

Reactor materials are well covered in the 19 papers of Section 2, both fuels and structural materials being dealt with. Irradiation effects in uranium and a number of structural materials are covered and the properties of alloys are also considered.

Section 3 contains new items on reactor technology, six papers being on component design and fabrication technique, and three covering reactor design of the APPR, the SRE and the G.E. Dual Cycle Boiling Reactor. The section concludes with two papers on the bibliography of nuclear technology.

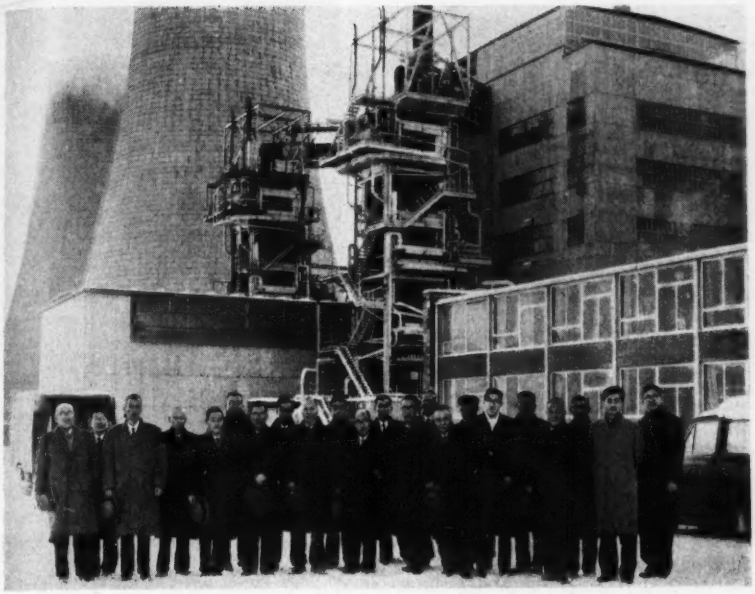
Heat Transfer is the subject of Section 4, in which there are five papers dealing with water as a reactor coolant. It commences with a paper on heat liberation rates of interest to component designers. A good paper on a boiling heat transfer experiment and its problems is followed by a paper on the flow sensitivity of a system of parallel channels. The fourth paper considers these and other effects on reactor safety and methods of ensuring safe operation at maximum power. Finally, heat transfer measurements for water flowing parallel to a rod bundle are given.

The Volume II papers are also grouped into four sections. Section 1 on Waste Disposal and Radiation Hazards contains 10 papers presenting a clear account of the present status of radio-active waste disposal in the U.S.A. (albeit with some repetitions) and a short general paper on Health Physics.

Chemical processing of reactor fuels is dealt with in Section 2. It commences with papers on the dissolution of solid fuel elements and the separation of bred fissile material from fertile, and the removal of fission products from both in thorium and uranium. A paper on radiochemical plant design gives an adequate introduction to the philosophy of plant design for direct maintenance. A fairly detailed report on flooding characteristics of a pulse extraction column is followed by papers on the processing of two homogeneous reactor fuels, aqueous U233-Thorium and U233-Bi. The advantages of pyrometallurgical processing for the removal and concentration of the bulk of fission products are shown but the final problem of producing fuel elements from the still radioactive material is not discussed. Liquid metal extraction and electrorefining is dealt with. A paper on processing using uranium hexafluoride is followed by a report on the pilot plant developed for this purpose. Further papers on methods of extraction using fluoride volatility differences, complete the section.

Section 3 is on experimental and critical assemblies and Reactor Physics. Nine papers offer a fairly representative picture of the methods of reactor physics research. A sub-critical pile for nuclear quality testing is described followed by a paper on chemical methods of checking the physical evaluation of reactor parameters.

Seven papers of general interest in the field of instrumentation and control are presented in Section 4. A description of the Canadian NUR instrumentation emphasizes the desirability of eliminating the unreliable thermionic valve by the use of cold-cathode trigger valves and pulse techniques where possible. Methods to obtain maximum reliability when thermionic tubes have to be used, are discussed. The problems of measuring neutron fluxes against a high gamma background are mentioned with descriptions of instruments following the conventional pattern of either chamber compensation or electronic discrimination. This is further discussed in a general paper on reactor controls and instrumentation and the control of a complete plant is well presented. A short paper on the control of a heavy water moderated, massive fuel reactor is followed by a useful method of calculating control rod effects and finally power and temperature control of pressurized water reactors is studied. D.W.J.-L.



Members of the Japanese atomic power delegation currently visiting Britain to see atomic energy electricity generating plant and equipment with a view to buying plant, photographed during a visit to Calder Hall. From left to right are:— Messrs. Ipponmatsu, vice-president of the Japanese Nuclear Power Company; Takai, president of the Tokyo Electric Power Co.; Fukuda; Sekimoto; Yoshioka; Watanabe; Tsuhimoto; Sayeki; Takeuchi; Haki; Yasukawa, President of the Japanese Nuclear Power Company and leader of the party; Kawabta; Kawamura; Muto, Professor at Tokyo University; Shimamura; Nasu; Sakuma; Risada, of the Building Research Institute; Sagane, vice-chairman of the Japanese Atomic Energy Research Institute; Naito; Umeda and Otsuki.

World News

The Board of Governors of the International Atomic Energy Agency, in its series of meetings held in Vienna between January 13 and 21, dealt with technical problems and plans for the implementation of certain major tasks of the 1958 programme of the Agency.

The Board gave much attention to the Agency's programme for exchange and training of scientists. The U.S.A. and the U.K. indicated that they would make substantial voluntary contributions towards the Agency's $250,000 fellowship programme. Notifications were given by Poland, Rumania, the U.S.S.R., the U.S.A. and Yugoslavia that they would place additional fellowships and training facilities at the Agency's disposal. I.A.E.A. will also study the establishment of a regional training centre in Latin America.

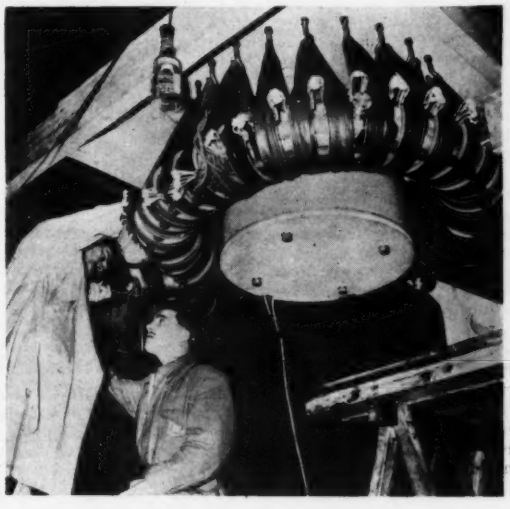
The Board discussed measures to ensure that the Agency will be able to carry out its statutory obligations concerning health and safeguards including the establishment, or adoption, of standards in this field.

So far as assistance to less developed areas was concerned, the U.S.A. indicated that it would offer on a cost-free basis the services of a number of expert scientific and engineering consultants who, along with consultants supplied by other members, would be available, at the disposition of the director general, to assist member states in the evaluation and formulation of their programmes or projects. The next series of meetings of the Board is scheduled to begin on March 10. This series will be concerned largely with the implementation of the Agency's 1958 programmes as well as with a preliminary discussion of projects for 1959.

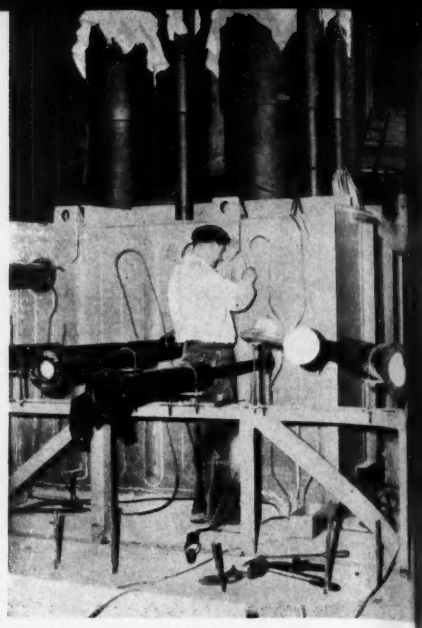
Nuclear Materials. Up to the end of January nine members of I.A.E.A. had offered to supply nuclear materials to the Agency. Canada for example offered several years' supply of natural uranium for Agency programmes. Ceylon: 30 tons of refined monazite of about 9% thorium content. India: all the thorium necessary for Agency programmes. Norway: isotopes, niobium, aluminium and molybdenum. Portugal: 100,000 kg of uranium oxide concentrate. Union of South Africa: uranium oxide concentrates, beryllium, lead, tantalum, cadmium, lithium, vanadium, chromium and nickel. U.S.S.R.: 50 kg of contained U235 in any concentration up to 20% together with supplies of further fissionable and other materials. U.K.: 20 kg of contained U235. U.S.A.: 5,000 kg of contained U235 together with nuclear materials equal in quantity to any other member of the Agency until July, 1960. In addition to these materials, financial, technical and educational assistance have been offered by several countries.

Release of information on ZETA by U.K. A.E.A. (page 95 this issue) was enthusiastically received by the world's press. The hard-working press officers at the Authority's head office were kept busy for several days with requests for further data and photographs. The release had the effect of making many countries divulge brief details of their own thermo-nuclear research activities. Experiments are also being carried out by the United States, U.S.S.R., France, Sweden and Japan. Norway is to carry out thermo-nuclear research under the direction of Dr. Tberhard Jensen and Professor Svein Rosseland. In West Germany, the Max Planck Institute for Physics is to start experiments soon.

Joint U.S.-U.K. conference to exchange classified information on research in the field of controlled thermo-nuclear reactions was held at the Naval Research Laboratory, in Washington, D.C., from February 3 to 5.



The French Atomic Energy Commissariat have successfully carried out experiments towards thermonuclear fusion, at temperatures in the region of 1,000,000°C. The experiments were carried out at the EDF Laboratories at Fontenay-Aux-Roses, near Paris. The device used (right) was a circular tube, some 9 ft. in circumference, called Equator.



(Above) During January the deputy directors general of the International Atomic Energy Agency were sworn in at the Vienna headquarters. (Left to right): the interpreter, Mr. Bernstein; Professor V. V. Migulin of the U.S.S.R., head of the department for training and information; Mr. Sterling Cole, director general; Dr. Paul Jolles of Switzerland, head of the administration dept.; Mr. Hubert de Laboulaye of France, head of the department for technical operations.

(Right) First phase in the construction of a research reactor at the Institute for Nuclear Research in West Berlin. The reflector tank has been set up and small-bore copper pipes for cooling purposes are being placed in the concrete shield. The solution-type reactor is being supplied by Atomics International.

The exchange of information was under provisions of the agreement for co-operation on civil uses of atomic energy between the two countries. The last meeting of this kind under the bilateral agreement took place at Princeton University on October 17-18, 1957. This is the sixth such meeting since the co-operative programme between the two nations was inaugurated in October, 1956.

Eurochemic, the new European company for the chemical processing of nuclear fuels, held its first conference at the end of January. Chairman of the meeting was Dr. Erich Pohland, of the Federal German Ministry of Atomic Affairs and the vice-chairman was Dr. Erik Svenke, head of the industrial division of the Swedish Atomic Energy Corporation. It was decided that a first team of personnel should prepare the final plans of the plant and also start preliminary research work at the Belgian Centre for Nuclear Studies in Mol.

Common European regulations for third party liability in the field of atomic energy are being discussed by an O.E.E.C. group of experts of the newly set up European Nuclear Energy Agency. The group has held its first meeting in Paris under the chairmanship of Mr. Adriaan Belinfante of the Netherlands Ministry of Justice. The vice-chairman is Switzerland's Professor Otto Kaugmann, one of the authors of the draft Swiss Atomic Law. Plans are to draft common regulations, perhaps in the form of an international convention, laying down a special régime which will ensure the harmony of legislation relating to third party liability and nuclear risks in the different countries.

Fourth (and probably final) session of the United Nations scientific committee on the effects of atomic radiation began during the last week of January. The committee was originally intended to present its report to U.N.O. General Assembly by July 1, but last November the Assembly asked that the report be expedited.

United Kingdom

In the event of a new site being required for further expansion, the U.K.A.E.A. will recommend Chapelcross. The Authority recently said that they had examined a number of possible sites with the object of reducing the lengthy period normally required for site clearance. Two reasons determine their choice of Chapelcross, (a) the site is already partially developed which would mean a substantial initial saving, (b) exploitation of a completely new site would require the services of extra senior managerial staff. The Authority point out that it does not have a particular project in mind and that planning permission would still have to be sought.

A public meeting attended by several hundred people on February 10 pledged support for the siting of a nuclear power station at Trawsfynydd. The public inquiry into the Central Electricity Generating Board's scheme opened on the following day.

Legislation for licensing and regulating inspection and control of nuclear reactors in the interests of public safety is being prepared by the Government. Sir Ian Horobin, parliamentary secretary, Ministry of Power, in a written reply on February 10 stated that all owners of reactors would be subject to the same duty as the Atomic Energy Authority of preventing damage to property or personal injury from radio-active contamination. A reactor owner will be required to insure his liability or to show that he is holding adequate liquid assets. The limit of liability will be £5 million in respect of each installation. This will apply to land-based reactors only because the insurance of reactors in ships, submarines and aircraft requires further study having regard to international aspects.

Argentine

Argentina's first nuclear reactor became critical on January 20. The ceremony was performed by the President, Mr. Pedro Aramburu. The 10-kW reactor, for experimental purposes, was built by the Argentine A.E.C. from drawings supplied by General Electric of U.S.A. The cost was less than 4 million pesos (about £40,000).

Australia

HIFAR—High Flux Australian Reactor—at Lucas Heights near Sydney, is now well ahead of the construction schedule. According to our correspondent the reactor diverged on January 26 and is now undergoing trials.

Belgium

Work on many of the large national pavilions at the Universal and International Exhibition which opens in Brussels in April is now almost complete. The British contribution will cost up to £3 million. At a recent conference in London, organized by the Federation of British Industries, a spokesman said that with the assistance of the Board of Trade and U.K.A.E.A. it was hoped to feature photographs, materials or equipment associated with ZETA.

Brazil

Brazil is the first nation to receive a cash grant as part of the United States Atoms-for-Peace programme of financial assistance for research reactor projects of friendly nations. The payment, a cheque for $350,000, was made in respect of the 5MW (T) pool-type reactor which went critical at Sao Paulo University last September. The unit was designed and built by Babcock and Wilcox (U.S.A.).

Colombia

I.C.A.N.—Instituto Columbia de Asuntos Nucleares—and Atomic Energy of Canada, Ltd., have agreed to exchange technical information on nuclear energy. The Compania Minera de Uranio hopes to begin commercial production of uranium oxide within a few months.

West Germany

R.W.E.—Rheinisch-Westfälisches Elektrizitätswerk A.G.—will probably limit itself to the purchase of an experimental power reactor in the 10 to 15 MW range, Herr Schöller, a director of the company, told the annual meeting. He commented that the company has been in touch with four British groups manufacturing nuclear power reactors, but they were still not satisfied that the stations would be economic. Detailed costs will be made available in a month or two and the company would then consider an investment of about £30 million for the construction of a 250 MW station.

Dedication of the 1-MW pool-type reactor at Garching, about 10 miles from Munich, took place on February 3. The reactor—designed and built by AMF Atomics Division, U.S.A.—is the main item of equipment in the new University of Munich nuclear research centre.

Japan

The Atomic Ship Study Council, a Government agency, has now received four schemes for nuclear-powered vessels. Plans have been submitted by Mitsubishi Heavy Industries, Kawasaki Heavy Industries, Harima Dockyard and Tokyo University and a group comprising Ishikawajima Shipyard, Hitachi Shipyard, Mitsui Shipyard, Japan Steel Tube Co. and the Maritime Safety Agency.

Mr. Matsutaro Shoriki, chairman, Japanese A.E.C., said on January 21 that it was hoped shortly to conclude agreements with Britain and the U.S. on imports of nuclear power reactors and fuel.

New Zealand

U.K.A.E.A. is negotiating with the holder of the uranium mining rights in the Buller Gorge area, Mr. F. Hackett, Minister of Mines, announced on January 29.

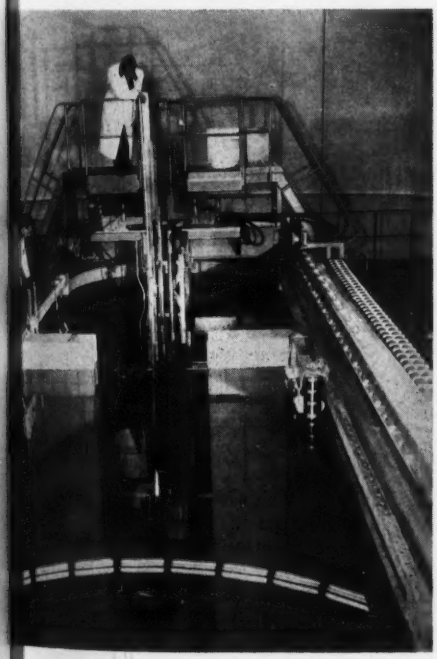
Poland

U.S.S.R. will provide technical assistance towards the construction of Poland's first nuclear power station, according to a new agreement between the two countries. In addition, Poland will receive help in designing and building a second experimental reactor, in prospecting, mining and processing uranium and in training nuclear scientists. Poland's first research reactor is scheduled to go critical at the end of March.

South Africa

British and American representatives of the Combined Development Agency have been invited by the Union Government for talks on the uranium programme.

Joint Committee for Nuclear Research has been formed by the Universities of Cape Town and Stellenbosch with a view to establishing a central institute. Amongst the projects under consideration is the purchase of an experimental reactor. Secretary of the committee is Dr. E. van de Spuy, senior lecturer in physics, Stellenbosch University.



Main laboratory tool of the University of Munich nuclear research centre at Garching is this 1 MW pool-type reactor which was dedicated on February 3. The reactor was supplied by A.M.F. Atomics, U.S.A.

Just outside the main fence at A.E.R.E., Harwell, work is in progress on the Rutherford high-energy laboratory. The photograph shows the excavation for the magnet and experimental area. The main contract for the work has been awarded to W. E. Chivers and Son, Ltd.

U.S.A.

A.E.C. intends to negotiate contracts with Curtiss-Wright, General Electric and a team consisting of General Motors and the Nuclear Development Corporation of America to perform studies on compact nuclear reactor systems for military use. The concerns were selected from among 28 organizations which submitted proposals to make these studies in response to an invitation of the Commission last October. The purpose of the studies is to determine nuclear reactor concepts which show most promise for use in military applications demanding a mobile power plant with moderate power rating up to 2 MW net electric output.

Three nuclear submarines—each capable of firing the Polaris intermediate range ballistic missile—were ordered by the Government on February 13. The vessels will weigh about 5,600 tons and have a very high underwater speed.

General Dynamics Corporation are to undertake the development of a prototype gas-cooled reactor, closed-cycle gas turbine plant for merchant ship propulsion. The project is contingent on negotiation of an acceptable contract by the AEC and the Maritime Administration. The initial phase of the project, to be known as the maritime gas-cooled reactor (MGCR), will include development of high temperature fuel elements reactor controls, selection of the proper coolant and moderator and comparable turbine machinery. Upon a successful conclusion of this development work, the design and fabrication, erection and test operations of a prototype plant will be undertaken. It is estimated that it will take from five to seven years from the time the initial contract is awarded to complete construction of the plant.

Advanced nuclear reactor concept to produce economic electric power is to be studied by Atomics International, a division of North American Aviation, Inc., for the Southwest Atomic Energy Associates, according to an agreement reached between the two organizations. The agreement calls for a $5,354,000, four-year research and development programme by Atomics International to determine the economic feasibility of the Advanced Epithermal Thorium Reactor (AETR) concept with a view to the construction of one or more full-scale power plants utilizing the AETR as a source of energy. The Southwest Atomic Energy Associates is made up of fifteen electric companies in Arkansas, Kansas, Louisiana, Mississippi, Missouri, Oklahoma and Texas. The AETR envisaged will use sodium as a coolant to transfer heat from the reactor core, uranium 233 as fuel and, if moderated, beryllium or graphite as a moderator. The nuclear power plant would be rated at approximately 200 MW. In this concept, thorium is converted to uranium 233, which, added to uranium originally placed in the reactor, provides the fuel which produces usable heat. Epithermal refers to the intermediate speed, not slow or fast, of the neutrons in the reactor.

More than thirty of America's leading scientific, engineering and professional societies are participating in the 1958 Nuclear Congress, to be held from March 17 to 21, at the International Amphitheatre in Chicago, Illinois. The Congress will be in effect an assembly of the fourth Nuclear Engineering and Science Conference, the fourth International Atomic Exposition, the sixth Hot Laboratories and Equipment Conference and the National Industrial Conference Board's sixth Atomic Energy Industry Conference. In addition, the National Industrial Conference Board in conjunction with the Atomic Industrial Forum will jointly sponsor an Atomic Energy Management Conference as a part of the Congress and the Atomic Industrial Forum's " Atomfair " will also be held.

Nearly 200 U.S. industrial concerns began using radioactive material for the first time in 1957, according to " The Atomic Industry, 1957," the annual progress report compiled by the staff of the Atomic Industrial Forum.

A.E.C. Licences and Permits. To General Electric, an amendment to power reactor development licence No. 1 permitting an increase in the thermal power level of the Vallecitos BWR from 20 MW to 30 MW. To Aerojet General Nucleonics of San Ramon, California, for construction of a 1 W pool-type reactor for training and demonstration purposes.

U.S.S.R.

Proton synchrotron of 50,000 MeV is being designed at the Institute of Electrophysical Equipment in Leningrad. According to a statement attributed to E. Komar, director of the Institute, this new machine will embody a rigid focusing system permitting a reduction in the amplitude of oscillation of the accelerated particles in their movement along the orbit, thus reducing the size of the vacuum chamber.

Orbits in Industry

NOW that the ballyhoo on ZETA has died down a little, Tangent's first reaction could be summed up in the words made so familiar by the B.B.C. . . . "What does the team think?" Do they, perhaps, echo this voice from the not-so-distant past?

"*Fifty years ago, nuclear physics was a happy hunting ground for scientists, where they could pursue knowledge for its own sake, without interference. When the atom bomb went off, that nice world was shattered. Those who work in atomic physics nowadays look forward to a pretty bleak future, in which everything they do and everything they say, and everything they think, is subject to scrutiny. . . . Nowadays it is scarcely possible for a physicist to blow his nose without exciting suspicion that he is about to destroy another city or—almost worse—to undermine the present economic fabric by suddenly presenting the world with a new power supply. . . .*"

These words—or something remarkably like them (because, after all, it was in 1946 and nobody can be word-perfect for ever) were spoken at the 37th Kelvin lecture by Professor M. L. Oliphant, himself an early worker in the fusion field. Do they ring a bell 12 years later?

Beware of the Bull!

No one in his senses (and even Tangent has his lucid moments in the dark of the moon) would attempt to belittle the achievements of the nuclear fusion team, who have achieved results which would have seemed fantastic only a short time ago. But their achievements can really be appreciated only by other scientists and to make a good story for the many-headed, it had to be subject to a considerable amount of "embelliflation."

Hear the Press's frenzied chorus
"Man-Made Sun!" . . . "The Magic Torus!"
——For the story some are telling
"Taurus" would be truer spelling.

Not the least of the team's achievements was to maintain their sense of proportion, while persuasive interviewers were trying to put words into their mouths. There must have been an overwhelming temptation to jump up and scream "Yes. . . . It's sensational! . . . In less than a year the coal mines will be closed down. . . . A new world is dawning! . . . I did it all myself. . . . Migawd let me OUT! . . ."

How they (and Sir John Cockcroft in particular, because he is always the sacrifice for the Roman holiday) must long for the days when one could deal with inquiries under the Official Secrets Act. Or Regulation 18B or something. Or even the simpler and more satisfying piece of lead piping wrapped in newspaper.

The Faraday Lecture

The I.E.E.'s Faraday lecture is always a "must" in Tangent's diary. For one thing, it is eagerly looked forward to by the young Sub-tangents (but not Co-tangent, who detests Science and all its works) and, for another, it is always an education in sheer showmanship; the presentation of highly technical concepts on a popular level. (One can hardly call it a non-technical audience, when about half the eminent men in the profession are present.) This year's lecture "Electrification of the British Railways," was held in rather unusual circumstances in that Mr. G. H. Fletcher, who prepared the lecture, unfortunately died before its London presentation and it was delivered by Mr. R. Ledger of the G.E.C. Traction Department, who very sportingly filled the gap. The subject itself is, of course, of marginal interest to the nuclear field, although the lecturer did point out that the electrification of the railways would save as much coal as the construction of 10 nuclear power stations (so that we may as well go out of business straight away—we can't compete on those terms).

A Nuclear "Faraday"?

The point (and there usually is one if you wait long enough) is, however, why doesn't the nuclear industry have its own Faraday lecture? It is true, of course, that two Faraday lectures have been devoted to atomic energy (both, incidentally, given by Dr. T. E. Allibone), but two lectures of this type in 10 years is not enough. That the public need educating in technical matters is only too obvious; that they like it when it is presented in a pleasant, easily digestible form is evident from the applause evoked at the Faraday lecture. Who is going to give it to them?

Before anyone hastily decides that it would be no trouble at all, let them look behind the scenes of the Faraday lecture. In the first place, an eminent personage, whose time is worth a great deal of money, devotes a lot of time to its preparation, and the design and construction of the ingenious demonstrations that are such a feature of this lecture. Next, when the show goes on tour, an exceedingly public-spirited company or organization loses the services of one of their top men and several assistants for at least a couple of months. This year's Faraday lecture "travels," to use the theatrical term, a troupe of nine, so there is also the question of accommodation and transport expenses. But it would be worth it.

R.P.D.

Speaking as one who (to borrow a phrase from P. G. Wodehouse) could not detect a bass drum in a telephone booth, Tangent has always had a considerable respect for research workers as such. He has, however, always tended to regard them as a kind of intangible asset, i.e., something nice to have around, but not susceptible to accurate costing—except, of course, the Alice-through-the-Looking-Glass variety ("Why, his time is worth a thousand pounds a puff!").

Modern thought, however, demands that everything should be evaluated in terms of pounds, shillings and pence—or, more frequently, in dollars, cents and mills—and we were reminded of this by the chairman of the U.S.A.E.C. in commenting on ZETA, when he pointed out that British scientists had achieved "more results per dollar" than their U.S. colleagues.

If R.P.D. is going to become a recognized criterion of research workers' efficiencies, then we must be able to express results in some absolute units—which we shall have to invent for ourselves. The motion-study boys have their "therbligs" and "winks"; the computer fanciers their "bits." Why should not research workers adopt the "scheme"? Since this, like the farad, would be inconveniently large (only to be costed in megaquids or gigabucks) subdivision would be required, and a suggested table would be

1 Scheme = 10 Sweats
1 Sweat = 10 Bashes
1 Bash = 10 Dabbles

Research workers could then be given an efficiency rating which had some meaning. In place of the imprecise I.Q. figure which everyone uses so glibly and so vaguely, scientists could be given an A.Q. (Achievements per Quid) rating in T.S. (Tangent Scale) units.

Further extension of the table may, of course, be necessary, to cover the smaller projects which result in discussions only, without any actual work done. Could we suggest, then, that the smallest unit should be again subdivided? One Dabble, for example, to equal 100 Natters? Or, say, 10 Yakkety-Yaks?

Tangent

Personal

Appointments

Sir William Cook.

Dr. B. F. J. Schonland.

Mr. D. W. Fry.

Sir William Cook, C.B., at present deputy director of A.W.R.E., Aldermaston, becomes a full-time member of the Authority in the first of a series of changes in the structure of A.E.A.

Sir John Cockcroft, A.E.A. member for scientific research and director of A.E.R.E., Harwell, is succeeded as director by **Dr. B. F. J. Schonland.**

Sir William Penney continues as a member of the Authority for weapons, research and development. Pending the appointment of a new director of A.W.R.E. he will continue to hold that post.

Mr. J. C. C. Stewart, formerly director of technical policy in the Industrial Group at Risley, as deputy managing director of the Industrial Group.

Mr. J. B. W. Cunningham, formerly deputy director (Civil Reactors), becomes director of industrial power in the Industrial Group.

Dr. R. Hurst, formerly chief chemist in the research and development branch of the Industrial Group at Risley becomes director of the Dounreay Experimental Reactor Establishment.

Mr. D. S. Mitchell, formerly director of administration, becomes director of personnel and administration in the Industrial Group.

Mr. D. W. Fry, chief physicist at Harwell, as deputy director, A.E.R.E.

Mr. Angus H. Campbell, C.A., divisional accountant of the North West, Merseyside and North Wales division since April, 1954, as deputy chief financial officer of Central Electricity Generating Board.

Mr. F. W. Fenning, as chief physicist, Industrial Group, U.K.A.E.A. in succession to **Dr. H. Kronberger** whose appointment as director of research and development we announced last month.

Dr. Frank E. Faris and **Dr. Lars C. Fischer-Zernin** as general manager of the technical department and general manager of sales, respectively, of Interatom, the first jointly owned international company in the German nuclear energy field. Interatom Internationale Atomreaktorbau GmbH. was formed recently by Demag AG of West Germany and North American Aviation, Inc., Atomics International Division.

Mr. Pierre Huet as director of the European Nuclear Energy Agency.

Mr. W. G. Tailyour as director, engineering sales, **Mr. H. Thorpe,** director home sales, and **Mr. T. B. Carey,** director export sales, of Chatwood-Milner, Ltd., a subsidiary of Hall Engineering Industries, Ltd.

Mr. D. P. Walton, secretary, and **Mr. H. H. Mullens** have been co-opted to the Board of C. A. Parsons and Co. Ltd.

Mr. W. Ralph Blakeborough as director, Glenfield and Kennedy Holdings Ltd. **Mr. F. A. Klouman** has relinquished his seat on the Board and has retired from his executive appointment with J. Blakeborough and Sons, Ltd., a subsidiary company.

Mr. A. J. Beanland as group sales director, Lancashire Dynamo Group Sales Ltd.

Mr. J. D. Farmer as deputy chairman and joint managing director of J. and E. Hall Ltd., following the death of **Mr. Victor A. Patterson. Mr. A. Greenfield** as joint managing director and **Mr. C. R. Croucher** as director of the same company.

International Atomic Energy Agency Appointments

Prof. Mario Eduardo Guido Bancora, at present scientific adviser for the secretariat of the IAEA and previously head of the dept. for physics, Argentine National Commission of Atomic Energy, to be director of the division of technical supplies.

Mr. John Edward Commins, at present scientific counsellor of the Australian Embassy, Washington D.C., to be director of the division of scientific and technical information.

Mr. David Fischer, at present senior officer for external liaison of the IAEA and previously first secretary in the South African Dept. of External Affairs, to be director of the division of external liaison.

Mr. Yoshio Fugioka, at present member of the Atomic Energy Commission of Japan, to be director of the division of isotopes.

Mr. Andrey Ivanovich Galagan, at present senior officer to the secretariat of the IAEA and previously counsellor of the Ministry of Foreign Affairs of the U.S.S.R., to be the representative of the IAEA with the United Nations.

Mr. U. L. Goswami, at present joint secretary, Ministry of Commerce and Industry, Government of India, to be director of the economic and technical assistance division.

Mr. Karol Kraczkiewicz, at present seconded from the secretariat of the United Nations as special consultant for personnel matters of the IAEA, and previously with the Polish Ministry of Foreign Affairs, to be director of the division of personnel.

Prof. Joaquim da Costa Ribeiro, at present head of the department of physics, Federal University Rio de Janeiro, Brazil, to be director of the division of exchange and training of scientists and experts.

Prof. Antonio Rostagni, at present director general of the National Institute of Nuclear Physics in Padua, Italy, to be director of the division of research, research contracts and laboratories.

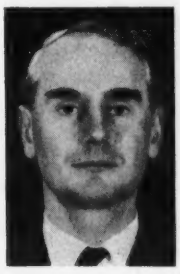
Mr. Josef Snizek, at present deputy minister of energy of Czechoslovakia, to be director of the division of reactors.

Mr. Donald G. Sullivan, at present seconded from the office of Dr. Ralph Bunche, under-secretary of the United Nations, head of the conference and general services of the IAEA, to be director of the division of general services.

Mr. G. W. Campbell Tait, at present head of the health physics branch at the Chalk River Laboratory of the Canadian Atomic Energy Commission, to be director of health, safety, and waste disposal division.

Mr. J. B. W. Cunningham.

Dr. R. Hurst.



Mr. D. S. Mitchell.

Mr. D. Clark.

Mr. G. C. Fairbanks.

Mr. H. Fox Wright.

Mr. W. Dalziel.

Mr. Dona'd Clark, B.Sc.(Eng.), A.M.I.E.E., A.C.G.I., station planning and development engineer, as chief planning engineer, Central Electricity Generating Board.

Mr. George C. Fairbanks, M.I.P.E., deputy general manager of Elliott Bros. (London) Ltd., as a director.

Mr. Arthur Cyril Yeates, M.I.Mech.E., M.A.Mar.E., A.M.I.E.E., as chairman of Crossley Premier Engines, Ltd.

Mr. E. E. R. Fuchs, M.I.E.I., A.I.Loco.E., as personal assistant to Mr. T. L. Kendall, sales director, Ruston and Hornsby Ltd.

Mr. A'exander Rubach as managing director of the newly formed Penco Research and Development Co. Ltd.

Mr. F. J. Clark has relinquished his appointments with the British Oxygen Group of Companies.

Mr. L. H. Cooper, chairman of The Mond Nickel Co. Ltd., and vice-president of The International Nickel Company of Canada, Ltd., as a director of that company.

Mr. W. D. Opher, M.I.Mech.E., and **Mr. R. P. H. Yapp** as special directors of Vickers Ltd. Mr. Opher also appointed as managing director Vickers-Armstrongs (Engineers) Ltd., on the resignation of **Mr. P. H. Muirhead,** C.B.E. Mr. Muirhead retains his other Group directorships but remains on sick leave.

Mr. K. W. Wagner as deputy chairman and joint managing director and **Mr. A. B. Davies** as joint managing director of the Sturtevant Engineering Co. Ltd., in succession to **Mr. W. E. N. Gwilt** who is retiring.

Mr. A. F. Appleton, formerly head of the Electronics and Vibration Laboratory of Bristol Aircraft, Ltd., as chief engineer, Benson-Lehner (G.B.) Ltd.

Mr. N. G. Worster, A.M.I.E.E., A.M.I.Mech.E., A.I.Loco.E., F.B.H.I., as chief development engineer of Measuring Instruments (Pullin) Ltd.

Mr. W. A. Burnside, A.R.Ae.S., as general sales manager and **Mr. J. Wardle** as contracts manager of the Electronic Machine Co. Ltd.

Mr. W. Carter as a director of Albright and Wilson Ltd. He was appointed the first managing director of the operating company, Albright and Wilson (Manufacturing) Ltd., last year. **Mr. K. A. M. Barton,** sales director, and **Dr. R. A. Gregory,** production director as joint managing directors of Midland Silicones Ltd. **Mr. S. Barratt** the former managing director was recently appointed chairman of the parent company, Albright and Wilson Ltd

Mr. J. C. Duckworth, B.A., F.Inst.P., A.M.I.E.E., deputy chief Engineer (nuclear power), has been appointed chief research and development officer of the Central Electricity Generating Board.

Mr. H. Fox Wright, contracts manager of The Plessey Co., Ltd., as an executive director of the company.

Mr. W. Dalziel, production manager of the Plessey Group, as an executive director.

Dr. Vannevar Bush, as chairman of Merck and Co., Inc., New Jersey, parent organization of Merck Sharp and Dohme International, manufacturing chemists.

Mr. Peter Elliott, general manager of Myton, Ltd., as a director. Myton, Ltd., is a member of the Taylor Woodrow Group.

Mr. L. A. C. Bartlett, A.M.I.Mech.E., takes over responsibility for the steering-gear division of George Kent, Ltd.; **Mr. R. S. Medlock,** B.Sc., A.R.I.C., A.M.I.Mech.E., A.M.I.E.E., as technical and home sales director. Mr. E. E. Cook, M.Inst.F., takes charge of a new central organization in Australia; he is succeeded as home sales manager by **Mr. J. Tham. Mr. W. T. H. Carter** becomes chief buyer for the instrument division.

Mr. G. F. Spicer as southern area representative for A.P.V.-Paramount Ltd.

Mr. B. A. Hensler, managing director of Siemens Edison Swan (Export) Ltd., as a director of Siemens Edison Swan Ltd.

Following the acquisition of the Fletcher Miller Group by C. C. Wakefield and Co. Ltd., **Mr. S. R. Miller,** chairman, Fletcher Miller Ltd., becomes a director of C. C. Wakefield and Co. Ltd., **Mr. A. George,** director and secretary, and **Mr. R. T. Miller,** director, Fletcher Miller Ltd., as directors of Wakefield-Dick Industrial Oils Ltd., and Messrs **J. C. Cragg, J. W. MacMahon** and **L. J. Windridge** of the Wakefield Group as directors of Fletcher Miller Ltd.

Mr. P. W. Howard, managing director, BTR Industries, Ltd., has been appointed deputy chairman.

Mr. Herbert A. C. McKay, B.A.(Oxon), of the Chemistry Division, A.E.R.E., Harwell, becomes director of the Bagdad Pact Nuclear Training Centre from July this year. He succeeds **Mr. W. J. Whitehouse** who was seconded from A.E.R.E. as director last year.

Tours

Rear-Admiral Hyman G. Rickover, U.S. Navy, and **Mr. H. Mandel,** naval reactor branch, U.S.A.E.C., visited the U.K. early in February for joint discussions with the Admiralty and the U.K.A.E.A. on nuclear propulsion for submarines. Visits were also made to several A.E.A. establishments, including Calder Hall.

Amongst the delegates at the sixth Scintillations Counter Symposium, sponsored jointly by the American Institute of Electrical Engineers, Institute of Radio Engineers, Atomic Energy Commission and the National Bureau of Standards, were **Mr. J. Sharpe,** B.Sc., A.M.I.E.E., chief engineer, valve division, E.M.I. Electronics Ltd., and Messrs. **A. E. Jennings** and **N. B. Balaam** of 20th Century Electronics Ltd.

Following the visit of the Canadian Trade Mission to this country in December, the Scientific Instrument Manufacturers' Association is arranging a Canadian tour of senior executives of leading British instrument manufacturers. Starting in Toronto in mid-March, the S.I.M.A. eight-man team aim to extend the goodwill created during the recent visit and investigate increasing trade in instruments between the U.K. and Canada.

Retirements

Mr. W. Glass has resigned from the Board of Telegraph Construction and Maintenance Co. Ltd.

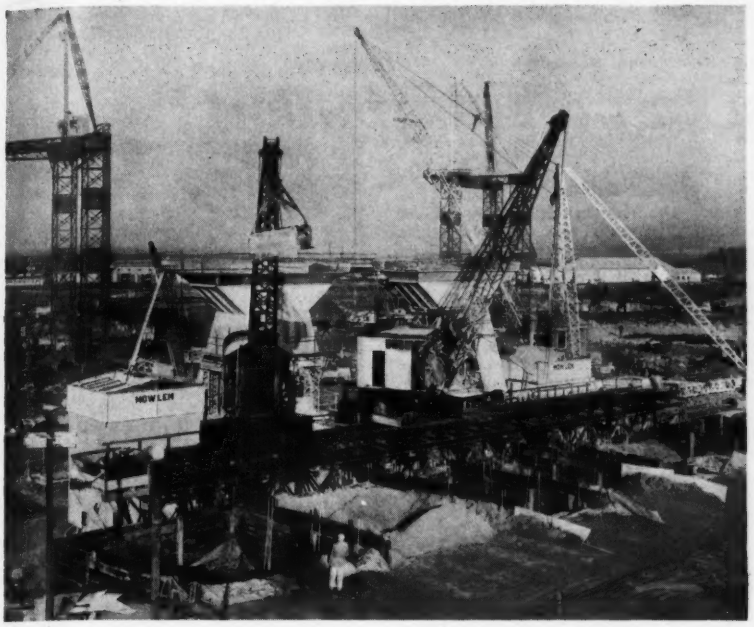
Mr. W. E. N. Gwilt, managing director of the Sturtevant Engineering Co. Ltd., retires at the end of April.

Mr. Hugh H. Baird has resigned his directorships of Baird and Tatlock (London) Ltd. and Hopkin and Williams Ltd.

Obituary

Nuclear Engineering records with regret the death of the following:—

Major F. H. Masters, O.B.E., T.D. M.I.E.E., who retired from the editorial staff of *Engineering* in September, 1956, died at Welwyn Garden City on January 29.



(Left) The concrete batching plant in operation alongside the site of reactor A at Hunterston.

Industrial Notes

At Hunterston, on the Ayrshire coast, some 70 acres of the site of Scotland's nuclear power station have been transformed, in the course of four months, into a scene of great activity with more than a thousand men at work. The station is being built for the South of Scotland Electricity Board by The General Electric Co., Ltd., in association with Simon-Carves, Ltd., The Motherwell Bridge and Engineering Co., Ltd., and John Mowlem (Scotland), Ltd.

So far attention has been concentrated largely on the foundations of the first reactor and the turbine hall. Having removed, on average, 8 ft of surface soil and green rock at the reactor base, blasting and excavation began on the foundations to cut out any faults and to produce a level surface prior to mass concreting. This mass concreting, involving the pouring of 3,000 cu. yd of concrete, has now been completed and work has started on the reinforced concrete raft above it. The raft will incorporate 8 000 cu. yd of concrete with 400 tons of reinforcing steel. Apart from the cranes already being used for transferring the concrete from the batching plant to the reactor base, two of the four derricks required for erecting the main concrete structure are now almost complete. The turbine-hall excavation, covering an area approximately 675 ft by 130 ft and going to a depth of about 13 ft, is now practically finished, and work has started on the cooling-water inlet culverts.

To ensure that the civil engineering activities can continue unhindered by work on the main steel structures, a complete workshop and prefabrication apron are being constructed on site. The workshop will be a twin-bay, steel-framed building served by two 40-ton travelling cranes. It is designed so that four steam-raising units, each 80 ft long and 20 ft in diameter, can be assembled simultaneously. The apron in front of the workshop will be used for the prefabrication of the six tiers of each 70 ft diameter spherical reactor pressure vessel before lifting them into their final position.

The workshop and apron are located on the centre-line of the two reactors so that the Goliath crane, which will be used for raising and placing the steam-raising units and pressure-vessel sections, will pass over these construction areas. This crane, which will be the outstanding piece of constructional equipment employed on the site, will have a height and span of 200 ft, so that it can straddle a completed reactor building, and will be capable of lifts up to 350 tons.

1958 British Electrical Conference.—The first overseas registrations for the conference—scheduled to be held in the Exhibition Auditorium at Brussels on May 16 and 17—have already been received and there has been a good response from the U.K. Sir John Cockcroft, director, A.E.R.E., Harwell, will present a paper "Nuclear Energy, the Power of the Future." Full details of the conference can be obtained from the Organizing Secretary, 1958 British Electrical Conference, 36 Kingsway, London, W.C.2.

Megator Pumps and Compressors Inc.—a subsidiary company of Megator Pumps and Compressors Ltd.—has been formed to market industrial and marine self-priming pumps in the U.S.A. Address of the new company is 930 Manchester Avenue, Pittsburgh 12, Pa.

Ferranti, Ltd., have already trained over 600 people on the Pegasus programming courses at their London computer centre at 21 Portland Place, W.1. Each course lasts a fortnight.

The Pulsometer Group have moved to a new London office at Pulsometer House, 20-26 Lamb's Conduit Street, W.C.1. Telephone: Holborn 1402.

Simms Motor Units, Ltd., have acquired a majority shareholding in **Motor and Electronics Corporation** and a new company with the title **Simms-M.E.C., Ltd.,** has been formed.

This month, for the first time, U.K.A.E.A. personnel in London will be housed together under one roof. The new premises are at 11 Charles II Street, S.W.1. The last of the offices to move, St. Giles Court, W.C.2, will be vacated on March 8. The new telephone number is Whitehall 6262.

Annual Congress of the Royal Society of Health will be held at Eastbourne from April 28 to May 2. The Minister of Health, Mr. Derek Walker-Smith, Q.C., M.P., has accepted an invitation to be president.

Meetings

March 3.—"Advanced Types of Power Reactor," by J. V. Dunworth, C.B.E., M.A., Ph.D., before the Mersey and N. Wales Centre, Institution of Electrical Engineers, Royal Institution, Colquitt Street, Liverpool, at 6.30 p.m.

March 10.—"Nuclear Radiation Hazards: Training of Local Authority and Hospital Personnel," by (a) Sir Ernest Rock Carling, F.R.C.S., F.R.C.P., (b) Mr. G. B. Courtier, B.Sc., D.I.C., F.R.I.C., and (c) Dr. W. H. P. Minto, before the Royal Society of Health, Caxton Hall, Westminster, London, S.W.1, at 2.30 p.m.

March 13.—"The Use of Nuclear Devices," by D. Taylor, M.Sc., Ph.D., before a meeting of W. Wales Sub-centre, I.E.E., at S. Wales Electricity Board Showrooms, The Kingsway, Swansea, at 6 p.m.

March 18.—James Forrest Lecture by Sir John Cockcroft before a meeting of the Institution of Civil Engineers, Great George Street, London, S.W.1, at 5.30 p.m.

March 18.—"Heat Transfer in Relation to Nuclear Engineering," by W. B. Hall, before a meeting of the North Western Branch, Institution of Chemical Engineers, Reynolds Hall, College of Science and Technology, Manchester, at 7 p.m.

March 25.—"The Atomic Clock," by L. Essen, D.Sc., Ph.D., before a meeting of the Measurement and Control Section, Institution of Electrical Engineers, Savoy Place, London, W.C.2, at 5.30 p.m.

March 26.—"The Objective for Euratom," by Professor F. Giordani, before a meeting of the Supply Section, Institution of Electrical Engineers, Savoy Place, London, W.C.2, at 5.30 p.m.

March 27.—"Housing the Dounreay Fast Reactor," by N. T. Barrett, B.Sc.(Eng.), A.M.I.Struct.E., before a meeting of the Institution of Structural Engineers, 11 Upper Belgrave Street, London, S.W.1, at 5.55 p.m.

Processes and Equipment

Semi-automatic Inert Gas Welding

In shielded inert gas metal-arc welding, a consumable bare electrode is fed at a controlled rate into the molten pool while a continuous shield of inert gas protects the pool and the metal in the arc from contamination by the atmosphere. No flux is required, there is no slag to remove, and the even metal transfer ensures neat, smooth welds.

Quasi-Arc have developed new semi-automatic equipment for this type of welding. Known as the Lynx, the equipment offers many new features, including a self-contained welding rectifier, a light and portable wire feed and control unit, with motorized remote wire-feed speed control, and a choice of water-cooled or air-cooled guns.

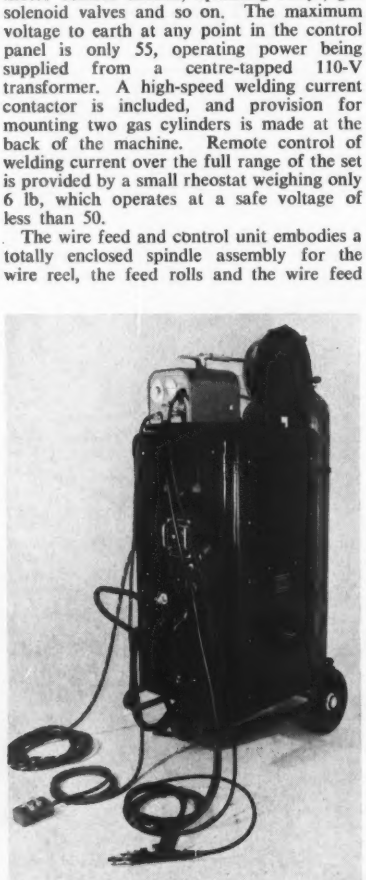
The welding rectifier is a specially developed power source consisting essentially of a combined transformer and selenium plate metal rectifier. The set includes a built-in control panel containing the wire-feed motor control circuits, operating relays, gas solenoid valves and so on. The maximum voltage to earth at any point in the control panel is only 55, operating power being supplied from a centre-tapped 110-V transformer. A high-speed welding current contactor is included, and provision for mounting two gas cylinders is made at the back of the machine. Remote control of welding current over the full range of the set is provided by a small rheostat weighing only 6 lb, which operates at a safe voltage of less than 50.

The wire feed and control unit embodies a totally enclosed spindle assembly for the wire reel, the feed rolls and the wire feed motor. The unit has been designed for portability; it weighs only 40 lb. A welder, unaided, can easily reposition it around large fabrications; for longer distance the spindle assembly and reel of wire can be readily slipped apart to form two separate sections, the heavier one weighing only 30 lb. Motorized remote control of the wire feed speed means that all adjustments can be made without loss of time. Wire-feed speed range is 60 to 600 in. per minute, and the controls can be operated with the gloved hand. The control circuits operate at a safe 24 V a.c.

The welding unit can be used with a water-cooled gun for currents up to 600 amp, or with an air-cooled gun for currents up to 300 amp (250 amp continuous). The air-cooled gun enables the equipment to be used on sites where water-cooling is difficult to arrange. The water-cooled gun incorporates a water-supply failure device and this protection cannot, therefore, be left out of circuit when the gun is fitted to the machine. This device automatically resets when the water supply is restored. The electrical connections to the gun operate at 24 V a.c.

The Lynx equipment is designed for welding aluminium and its alloys, copper and its alloys, corrosion-resisting steels, mild steel, and so on. Welding speeds are high: in aluminium, using $\frac{1}{16}$-in. wire at a current of 245 amp, a $\frac{1}{4}$-in. horizontal-vertical fillet weld can be deposited at an overall welding speed of 18 in. per minute.

(Quasi-Arc, Ltd., Bilston, Staffs.)



The Lynx carriage unit and welding rectifier.

Gas Refrigerating Unit

Philips Electrical, Ltd., announce that their gas refrigerating machine is now available in a new version—the P.W. 7000. In its new form, it is a compact, electrically driven, single-cylinder unit, capable of producing five litres of liquid air or liquid nitrogen an hour, within 15 minutes of starting up. The design of the equipment is unique in that the gas to be liquefied does not undergo compression or pass through any working parts; by this means an exceptionally pure product is assured. The machine will produce liquid gas from those gases which will liquefy at above −200°C, and temperatures of −80°C to −200°C can be achieved in a single stage. Under normal conditions the machine requires only one hour for defrosting and draining of the freezer after 16-20 hours production. Moisture and carbon dioxide are removed simply by freezing.

Other attractive features of the P.W. 7000 include small dimensions and light weight compared with conventional plants, continuous operation without supervision, and automatic operation after starting up; fully protective safety devices against abnormal conditions; low operation costs in relation to the quantity of liquid gas produced.

(Philips Electrical, Ltd., Century House, Shaftesbury Avenue, London, W.C.2.)

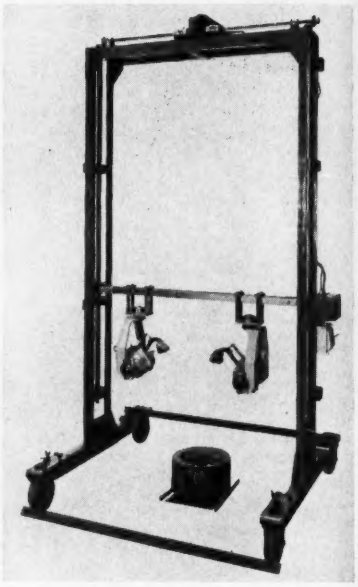
New Temperature Recorder

Ether Ltd., have now added to their range of instruments a temperature recorder capable of handling up to six independent temperature points. The recorder incorporates a conventional galvanometer, a chart and chart-drive mechanism, recording mechanism, automatic ribbon mechanism and an automatic station selector and indicator.

The recording chart has a calibrated width of 6 in. At a speed of 1 in./h it runs continuously for 30 days and it will also run at speeds of $\frac{1}{2}$ in. or 2 in./h if desired. The chart is fed over frontal nylon drive wheels powered by a synchronous electric motor of 220-250 V which also drives the recording mechanism. Easy loading is ensured by the presence of a hinged front top plate which pulls down and gives access to the chart roll.

A lightweight "chopper-bar," with calibrated scale attached, is located above a knife-edged galvanometer-pointer. Through the action of a timing cam and gear-train, the chopper-bar strikes the pointer at given intervals and imprints a small, coloured dot through the ribbon on to the recording chart. The knife-edged pointer is attached to the galvanometer coil by means of a flexible metallic strip which reduces the disturbance and load to the precision-ground pivots at the impact of the chopper-bar.

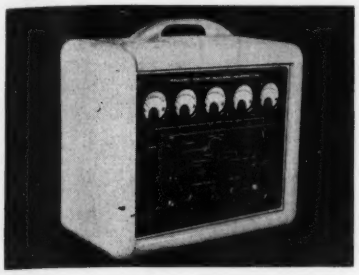
The galvanometer is fitted with an



Heavy-duty Emefco type M2/51 stereo-gamma-radiographic equipment capable of using two cobalt-60 sources of 700 millicuries each for the determination of flaw depths in heavy castings. Stereographs are taken on a single film using twin Gamma-Rays machines type ASS/51. With a free span of 1 metre and a free height of two metres, the unit can be wheeled over extremely large pieces. Manual operation is used for the setting of angles and the distance between isotope sources; height adjustment is electrical. Full referencing is possible through engraved scales giving distance between isotopes and all angles in space. The unit shown was supplied for installation at Brodoimpeks, Yugoslavia. (Nuclear Research Applications, Ltd., Emefco House, Bell Street, Reigate, Surrey.)

Alcomax II magnet, a high-resistance coil, precision-ground hardened pivots and spring-loaded polished sapphire jewels, all of which help to ensure an accurate performance even under severe operating conditions.

(Ether Ltd., Tyburn Road, Birmingham.)



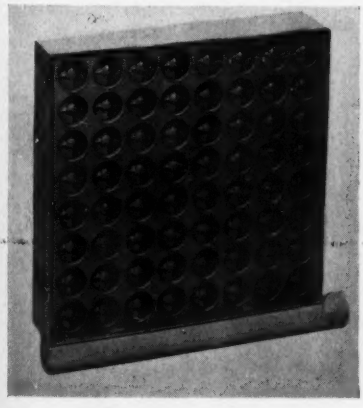
Transistorized frequency and time measuring unit, TSA 3, by Venner Electronics, Ltd., New Malden, Surrey.

Air Filters

Intermit, Ltd., one of the Birfield group of companies, are manufacturing the "Far-Air" and "Rotonamic" filters under U.S. licence. The Far-Air filter is constructed of fine wire mesh formed in alternate layers of flat and herring-bone crimped, making triangular channels set an an angle to the air flow, so that the air is divided into small turbulent streams and the particles impinge on the mesh which is coated with a viscous oil. The particular point about the Far-Air principle is that the entrapping of the particles does not all take place on the up-stream face of the filter but automatically moves to a slightly different spot through the depth of the filter as progressive clogging occurs, giving a considerable increase in life without excessive pressure drop. The filter units are supplied in 2-in. and 4-in. thickness, in standard sizes of 16 in. by 20 in., or 25 in., and 20 in. by 20 or 25 in. Self-cleaning filter assemblies can be provided or a cleaning and replacement service is available. Efficiency is given as 99% down to about 14 microns, and 88% at 4 microns.

The Rotonamic filter is a multiple assembly of miniature cyclones, there being 64 in a 20 in. by 20 in. panel, with a thickness of just over 4 in. and efficiency on high-density dust (such as powdered iron) is said to be 96% on the 0.6-6.0 micron particle range.

(Intermit Ltd., Bradford Street, Birmingham, 5.)



Rotonamic filter panel. Solid particles are aspirated through the tubular section at the base.

New Scanning Unit

The I.D.L. scanning unit, type 701, employs a strip chart recorder for automatic plotting of pulse height spectra, in conjunction with scintillation counting equipment incorporating a single-channel pulse analyser and a ratemeter. The chart recorder drum is direct-coupled to a 355° potentiometer. This varies the discriminating voltage of the pulse analyser, while the pen movement (controlled by the ratemeter) follows the corresponding pulse rate. The scanning time can be switched to 10 minutes or one hour, and the chart length per scan is 6 in. Each 6-in. record represents a scan over either the complete voltage range or the upper half of the voltage range, as selected by a two-position switch.

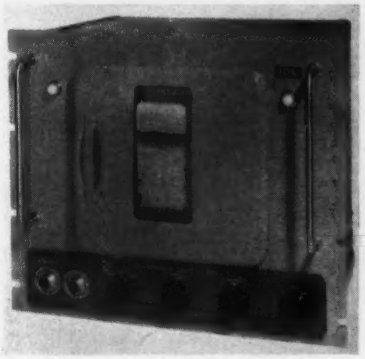
The servo-type precision 10K potentiometer has a linear accuracy of ±0.5%. Calibration marks can be put on the chart at any required point by means of a switch which makes the recorder read full scale or zero. The exact zero of the potentiometer is indicated by means of a witness mark.

According to the position selected by switching, the instrument will either stop after a single scan or will scan repetitively. In either case a light gives warning of completion of each scan. Repetitive scanning is useful for studying the drift of characteristics with time.

Another switch permits the upper half of the normal scan to be separately expanded into a full 6-in. record, thus giving the equivalent of a 12-in. chart length per full scan. Pre-set potentiometers are provided for accurately defining the voltage scanned.

The instrument is designed for standard Post Office rack mounting with dust cover (front panel size 15½ in. by 19 in.), but is also suitable for bench use. Special features of the design include an unspillable inkwell for the recorder, and quick-drying ink which does not smudge or grow mould. Mains input plugs at the rear permit connection to existing equipment without the need for an extra mains supply point. The light-weight door swings completely clear or can be quickly removed to give easy access. A paper tear-off device is fitted, but the chart can hang freely through a slot in the bottom of the door, or can be wound onto a take-up spool.

(Isotope Developments, Ltd., Beenham Grange, Aldermaston Wharf, nr. Reading, Berks.)



Type 701 scanning unit by Isotope Developments, Ltd.

Graphite Bursting Discs

Powell Duffryn Carbon Products of Hayes, Middlesex, have now introduced a range of bursting disc assemblies in carbon and graphite. A bursting disc provides means by which pressure vessels or other plant are protected from over-pressure through the medium of a diaphragm of material weaker than the vessel structure itself.

The design of the holder and disc is such that replacement discs are easy to install and moreover, location of the disc in the holder is fool-proofed by means of the special slotted holder arrangement. The assembly clamps between pipework flanges adjacent to the installation to be protected.

The standard range is available in sizes, 2-in., 3-in., 4-in. and 6-in. bore. Pressures between 5 p.s.i.g. and 75 p.s.i.g. are offered and bursting accuracy is guaranteed within ±5% of the rated burst pressure. For discs rated 20 p.s.i.g. or below, vacuum supports of either bar or dial type are available if the possibility of vacuum conditions within the vessel exists. Working pressures may be up to 75% of the nominal burst rating. Special ratings are also available and the Hayes factory has recently produced for the U.S. market 6-in. discs rated at 1 p.s.i.g. vacuum for the protection of lead lining in process vessels under conditions of negative pressure.

The assemblies are completely resistant to the corrosive effects of a very wide range of contact materials and temperatures up to 160°C can be tolerated without deterioration of the physical properties of the disc or reduction in bursting accuracy.

(Powell Duffryn Carbon Products, Ltd., Hayes, Middlesex.)

Briefly . . .

New Universal pH meter test set by A. M. Lock and Co., Ltd., enables laboratory or industrial pH meters to be checked quickly and accurately. (A. M. Lock and Co., Ltd., Prudential Buildings, 79 Union Street, Oldham, Lancs.)

The Alnor dewpoint meter, manufactured in the U.K. by C. F. Casella and Co., measures water vapour density, water vapour pressure and proportion of water vapour by volume. (Electric Resistance Furnace Co., Ltd., Netherby, Queen's Road, Weybridge, Surrey.)

New Clorocel equipment for the continuous production of sodium hypochlorite for the sterilization of large quantities of water is now being marketed by the Paterson Engineering Co., Ltd. The sterilant is produced by continuous-flow electrolysis: the method is particularly suitable for the treatment of condenser water. (Paterson Engineering Co., Ltd., Windsor House, Kingsway, London, W.C.2.)

High sensitive photo-electric cell employing cadmium sulphide has been introduced by Mullard Ltd., Mullard House, Torrington Place, London, W.C.1.

Aluminium plate for general engineering purposes is now obtainable in widths of up to 11 ft. Hitherto the maximum width of rolled plate has been 7 ft, but Northern Aluminium Co., Ltd., of Banbury, Oxon. are now supplying wider plate formed by butt-welding two plates together.

Maxilume illuminators for examining radiographs of up to 14 in. by 17 in. (35 cm by 43 cm) have recently been introduced by Newton Victor, Ltd., the X-ray department of Metropolitan-Vickers. A feature of the unit is the use of 15-watt colour-matching fluorescent lamps which provide an evenly diffused light.

Patents Reviewed

These abstracts have been made from British Patent Specifications, complete copies of which can be obtained from the Patent Office, 25 Southampton Street, London, W.C.2, at 3s. 6d. each (including postage).

B.P. 783,094. Support devices for use in nuclear reactors. F. G. Greenhalgh, E. Long. To: U.K. Atomic Energy Authority.

For providing support for vertical columns of fuel elements and moderator material constituting the reactor core. The support must be resilient under impact by falling fuel elements and must accommodate differential thermal expansions between the base support members and moderator. Free movement of the supporting and locating means is ensured by a ball and cage assembly over the base member. A shear pin is inserted as a protection against damaging impact by a falling fuel element while cutting edges then scraping along the inner wall of a guide serve as braking means.

B.P. 783,195. Production of thorium compounds. J. M. Fletcher, G. J. Ashworth. To: U.K. Atomic Energy Authority.

Crude thorium hydroxide is dissolved in excess nitric acid and the acid solution boiled to break down any phosphate complexes. The resulting aqueous solution, with nitric acid present in at least molar concentration, is subjected to organic solvent extraction with tributyl phosphate containing a non-polar organic solvent as diluent.

B.P. 783,400. Liquid homogeneous reactor safety overflow system. I. F. Weeks. To: North American Aviation Inc.

A safety device for preventing radioactive contamination of the surrounding area by solution expansion and overflow during a reactor runaway. To entrap the surge overflow from the core the core container is connected to an accumulator of size such that the ratio of volume of the accumulator to the volume of the core container is greater than the ratio of the excess of fissionable material in the container (over the critical mass) to the total mass of fissionable material in the container. The overflow is physically separated from the solution in the core container, so that two subcritical masses of fissionable material are obtained.

B.P. 783,591/592. Recovery of uranium by ion-exchange. T. V. Arden. To: Permutit Co., Ltd.

Uranium can be removed in the form of a complex anion from solutions containing uranium salts (sulphates or phosphates) by treatment with an anion-exchange material in salt form. The uranium complex is then removed by further ion exchange in an eluting solution, usually an acid solution of ammonium nitrate or a mixture of sodium chloride and sulphuric acid. This known process (B.P. 626,882) can be used for the recovery of uranium in the form of a complex uranyl sulphate anion which is preferentially absorbed even when present only in low concentrations. Now cobalticyanide may be present in the uranium-containing solution especially when the ore under treatment is also a gold ore and has previously been treated with a cyanide solution. The affinity of cobalticyanide for the resins used in recent years, i.e., those containing quaternary ammonium groups, is so great that it is absorbed and cannot be removed by normal eluting solutions, thus preventing uranium uptake. It has now been discovered that certain resins have the properties both of taking up cobalticyanide and of releasing it again on treatment with a suitable solution, so as to allow continuous re-use. The best resin for this purpose is one containing a predominance of ethylamine groups attached to side chains. Others mentioned are those having predominantly benzylamine, ethanolamine and diethanolamine groups (783,591). The recovery process may also be carried out by passing the uranium and cobalticyanide containing solution in contact with a separate mass of anion-exchange material in salt form (filter for cobalticyanide) which mass is replaced when it will no longer trap the cobalticyanide while the mass by which the uranium is removed is periodically eluted and regenerated (783,592).

B.P. 783,601. Recovery of plutonium from solutions containing it. To: U.K. Atomic Energy Authority (U.S.A.).

A method of separating plutonium (small amounts) from neutron-irradiated uranium (large quantities) must be of such simplicity and ease of operation as to lend itself readily to remote control. The method consists of removing plutonium from solutions containing it in a lower state of oxidation than the hexavalent form by treating the solution with a fluoride of low solubility in water and which has the property of absorbing the plutonium. The absorbed plutonium is then removed by treatment with a soluble oxalate, carbonate or bicarbonate. Examples of suitable fluorides are calcium fluoride, strontium fluoride, lanthanum fluoride and other rare earth fluorides.

B.P. 783,628. Recovery of thorium from monazite. R. W. Blundell. To: U.K. Atomic Energy Authority.

The monazite is digested with strong sulphuric acid at elevated temperature. The pasty mass obtained is cooled and added to a large volume of water, the temperature being kept below 30°C. The mixture is then filtered and the filtrate heated to about 45°C and treated with ammonia solution to precipitate light rare earth metal double sulphates. The resulting mixture is again filtered, the filtrate then containing the greater part of the thorium.

B.P. 783,646. Zirconium ternary alloys. To: U.K. Atomic Energy Authority (U.S.A.).

A zirconium base ternary alloy containing 1 to 5 wt.% of niobium and 0.1 to 2% metals such as aluminium, molybdenum or vanadium, the weight percent of niobium present exceeding that of aluminium, molybdenum or vanadium. Such alloy possesses the tensile characteristics at high temperatures of stainless steel and satisfactory ductility but has capture cross-sections for thermal-neutrons less than one-third the capture cross-section of stainless steel.

B.P. 783,987. Process and apparatus for carrying out nuclear fission reactions. To: Stichting Reactor Centrum Nederland (Netherlands).

It is difficult to control the concentration of nuclear fuel suspensions in all parts of the reaction vessel in reactors working with solid fissile material in a carrier liquid. These difficulties are caused by the high specific gravity of the fissile material (natural or enriched uranium oxides) and the necessary high-temperature level in the heat exchanger, which means low viscosity of the carrier liquid promoting rapid settling of the fuel. These difficulties can be overcome if turbulence of the suspension is avoided while descending through the reactor vessel. Therefore the vessel is so designed that the suspension is conducted by a vertical passage or passages of uniform cross-section in laminar flow and the fissile material enters continuously the passage or passages in such concentrations in the carrier liquid that the concentration of the suspension considered along any vertical flow line within the passages is uniform. This means that the concentration may vary horizontally but is vertically constant at any place across the vessel.

B.P. 784,125. Production of radioactive isotopes. J. C. Charlton, C. C. Evans. To: U.K. Atomic Energy Authority.

Refers to the production of carbon 14 by neutron irradiation of nitrogen. An irradiated metal nitride is subjected to oxidation at elevated temperature by passing oxygen into contact with the heated nitride (aluminium nitride) in a vessel and passing the gases leaving the vessel through an absorbent or adsorbent for the carbon dioxide formed.

B.P. 784,126. Production of aluminium nitride. J. C. Charlton, C. C. Evans. To: U.K. Atomic Energy Authority.

When preparing aluminium nitride from its elements with the aid of a catalyst a massive or lumpy product may be obtained which is extremely difficult to reduce to a powder. In order to produce the material in a readily crushable form, the mixture of finely divided aluminium of high purity and catalyst (particularly potassium hydrogen fluoride) is heated in an atmosphere of nitrogen gas at a temperature below the melting point of aluminium until reaction between the nitrogen and aluminium sets in. The temperature is then raised above the melting point of aluminium to complete the reaction.

B.P. 784,161. Electric cables and insulated wires. L. G. Brazier, R. M. Black. To: British Insulated Callender's Cables, Ltd.

Use of high energy radiation before soldering of cable fitting to reduce risk of softening the body of the fitting.

B.P. 784,291. Nuclear reactors. E. Long, J. W. Ashley. To: U.K. Atomic Energy Authority.

Refers to a moderator structure having regard to Wigner growth (see *Nuclear Engineering*, December, 1957, pages 527/528).

B.P. 784,292. Moderator structures for nuclear reactors. E. Long, J. W. Ashley. To: U.K. Atomic Energy Authority.

(See above and also *Nuclear Engineering*, December, 1957, pages 527/528.)

B.P. 784,315. Electroscopes and gland seals therefor. D. F. Burnett. To: Rank Precision Industries, Ltd.

Portable (pocket) instruments for, e.g., measuring gamma- or x-radiation dosages. A reciprocal spring-loaded charging sleeve also loads a ring gland seal surrounding the sleeve, so as automatically to compensate for any relaxation of the seal.

B.P. 784,316. Electroscopes and charging mechanisms therefor. D. F. Burnett. To: Rank Precision Industries, Ltd.

Provision of an earthing resistance connected to the moving member of the charging switch in the retracted position of the switch so as to eliminate short circuiting.